Emilio Chuvieco
(Ed.)

# Earth Observation of Wildland Fires in Mediterranean Ecosystems

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Editor

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# Foreword

> If fire break out, and catch in thorns, so that the stacks of corn, or the standing corn, or the field, be consumed therewith; he that kindled the fire shall surely make restitution (Exodus, 22, 6).

Fire was one of the most precious instrument that humans learned to dominate in the early stages of civilization, a source of heat and light, an instrument for cooking and warming. It was such an indispensable component of the ordinary living that we have named our most private space to stay as the place where the fire consumes ("hogar", "fogar", "foyer", from the Latin name "focus", fire).

However, fire has not only be a house tool, but a powerful mean for extensive land clearing. The expansion of agricultural colonization has been commonly preceded and followed by biomass burning. As the human footprint extended, the Earth's vegetation has been shaped by fire, which is now a critical factor to understand ecosystems functioning worldwide.

The traditional uses of fire, molded by millennia of human-nature interrelationships, have recently been affected by sharp changes, both in the way humans use the land and in the climatic conditions that also impacted fires in natural cycles. New challenges in the interactions between fire and humans arise. Fire becomes not only a tool but also a risk, affecting human lives, properties and ecosystems at temporal scales where the impacts are more detrimental.

The Mediterranean has been a privileged scenario of this long history of human-fire relationships. Mediterranean climates are characterized by dry and hot summers, which create favorable conditions for fire outbreaks. The presence of fire is evident both in historic testimonies as well as in the shaping of Mediterranean vegetation communities, which are well adapted to fire impacts. However, recent changes in traditional human land uses and in climate conditions create new challenges for fire management. To review some of those new conditions and propose new tools to monitor them are the main objectives of this book.

The first initiative to edit this book came as a result of an offering from the Springer editorial to update the contents another volume I edited in 1999, named "Remote Sensing of Large Wildfires in the European Mediterranean Basin". In fact, this new text should be considered rather more as a new book than as an update, since the scope has been broadened and, as a result, most of the contributors

changed. Satellite Earth Observation techniques are still widely covered in this text, but additional chapters have been included to present a wider panorama of fire danger conditions and fire impacts on the Mediterranean. Among these new contributions are the chapters dedicated to fire propagation and fire emissions. Additionally, a global ecological context of fire has been introduced, along with the presentation of problems associated to fire management in other Mediterranean areas of the world (Chile and California).

The book includes 13 chapters and an extensive list of references, that are compiled at the end of the text to avoid duplications of the different chapters. Illustrations try to provide a visual image of some of the products generated by the proposed methods, as well as the impacts of fires in different Mediterranean landscapes. A separate plate section has been included with the color figures. They are quoted in the different chapters with an asterisk (∗).

I sincerely thank the effort of all authors to provide the most recent reviews on the different topics covered in the text. I hope the book will help fire managers, scientists and the general public to better understands fire risk conditions and fire impacts in Mediterranean areas, to reduce their negative effects and take advantage of their positive ones.

Alcalá de Henares, Spain  
February 2009

Emilio Chuvieco

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# Prelims

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# Chapter 1
# Global Impacts of Fire

**Emilio Chuvieco**

**Abstract** An analysis of global implications of fire is presented, both considering the effects of fire on vegetation and atmospheric composition at global scale, as well as the impacts of estimated climate and landscape change on fire occurrence patterns.

## 1.1 Fire as a Global Process

Fire is a natural factor that has shaped the Earth's vegetation throughout its natural history. The control of fire by humans has extended the influence of fire beyond its ecological limits, offering human beings a powerful tool not only for their warming and cooking, but also for protection, land clearing and soil fertilization.

The Food and Agricultural Organization (FAO) statistics on global impacts of fires are partial and, according to the organization, not very accurate for many countries (FAO 2007). For this reason, the best estimation provide by FAO is based on satellite estimations of burned areas. Two independent analysis of worldwide burned areas were carried out from satellite data for the year 2000. The estimation based on SPOT-Vegetation data, named GBA 2000, calculated a total amount of 350 million ha burned (Tansey et al. 2004), while the study based on ERS 2-ATSR images estimated a global amount of 200 million ha burned (Simon et al. 2004). With a longer satellite series Tansey et al. (2008) estimate between 350 and 440 million ha burned every year for the period 2000–2007. Based on different sources, Levine et al. ( 1999) estimated between 500 and 560 million ha burned annually worldwide. Fire is clearly a global issue, affecting almost all climates and vegetation functional groups. In a recent study based on a seven-year

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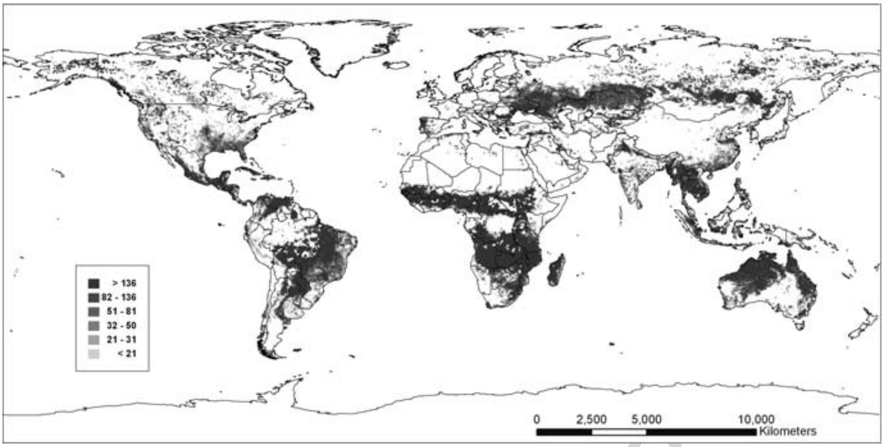


**Fig. 1.1** Average monthly density of fires detected from the MODIS sensor (in fire counts $10^{-5}$ km$^2$). Data have been grouped in 0.5×0.5 degrees cells (after Chuvieco et al. 2008b)

series of active fires detected from the MODIS sensor, Chuvieco et al. (2008b) estimated that more than 30% of the Earth's land area has significant fire activity (Fig. 1.1). Fire density is more intense in both tropical belts, north and south of the Equator, the former mainly in Africa and secondarily, in Latin America (Venezuela-Colombia and Central America), and South East Asia while the latter mainly in the Amazon and Congo basins, and North Australia. The global impact of sub-Saharan African fires is very evident, with extended areas in Central Africa, Gulf of Guinea and Angola-Zambia-Zimbabwe and Madagascar. Other tropical regions have intense fire activity, such as the agricultural frontiers in South and Central America, and Southeast Asia. Medium to high values of fire activity can also be observed in boreal forest ecosystems (Siberia, Alaska and Northern Canada). Lower values of fire density than those mentioned, but still relevant, are observable in SE United States, Central America, a long latitude strip between 45 and 57° N in Central Asia (Ukraine, South of Russia and Kazakhstan), and Far East Asia, although they should be associated to agricultural burnings (Korontzi et al. 2006). The Mediterranean areas do not account for a large proportion of burned areas globally, but all of them show significant fire activity, especially during the summer season.

Fire is a natural process, since it may be caused by natural factors, such as lightning or volcanic eruptions. However, at the global scale, fire is mainly controlled by human activities, which cause most fires directly or indirectly (FAO 2007), associated with various socio-economic activities. The estimated impacts of fires on people, infrastructures and natural resources are largely unquantified, although they are assumed to be enormous, including loss of human and animal lives, short and long-term effects on health, deterioration of timber resources, and indirect costs, such as those involved in fire suppression efforts, and the deterioration of natural and recreational resources (soil erosion, local fauna).

## 1.2 Global Factors and Effects of Fire

The global impacts of fire can be approached from analyzing its main factors and effects (Fig. 1.2). Historically, fire has been the simplest way to remove trees and shrubs for agricultural or grazing purposes. These transformations were permanent or cyclical, depending on the type of agricultural practice in place. For most tropical countries, shifting cultivation was the traditional form of farming (Spencer 1966). It implies the periodic removal of forest cover by fire by local communities. The cleared areas were fertilized from the provision of N and other nutrients as a result of the combustion process, and therefore the area could be cropped for a few years. The intense rainfall of tropical regions results leaching of nutrients from largely infertile soils and soil erosion, and therefore the agricultural yields decreased within a few years. As a result, farmers had to move to another forested area to start a new cycle, and from there on to another one, until they return to the original location in 30–40 years. In recent decades, these cycles have been shortened, as a result of a more intense land use and increasing populations, and therefore the crop production is increasingly degraded. Reduced agricultural yields, in turn, increases poverty and migration to urban regions.

A similar cyclical use of fire can be observed in savannah ecosystems, where grasses are burned annually to remove unpalatable grasses and to promote the growth of fresh grass for grazing (Van Wilgen 1997). For this purpose, millions of hectares are burned every year in central Africa and Latin America, which represent the most active fire areas in the world (Randerson et al. 2005).

The non-cyclical uses of fires are associated with movements of the agricultural frontier, which imply changing forested areas for permanent agriculture or cattle

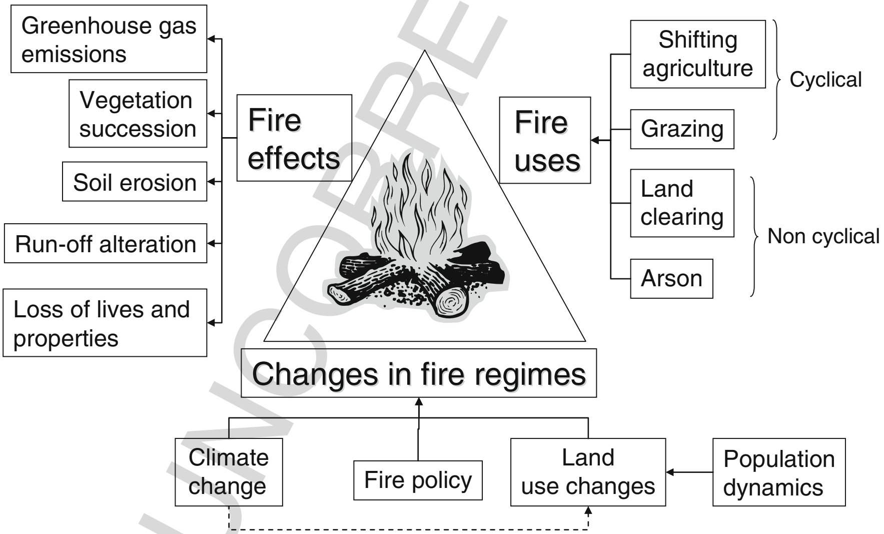


**Fig. 1.2** Global factors and impacts of Biomass burning (adapted from Chuvieco (2008)

ranging. This trend was very intense in the temperate forest of Europe during the early colonization and more recently in North America during the eighteenth and nineteenth centuries (Pyne 1995). Currently, the conversion of forest to agriculture or grazing areas is mainly occurring in tropical forests and woodlands, although boreal forests are affected by intense deforestation as well (Mollicone et al. 2006). Deforestation is one of the main factors to take into account in global carbon budgets, since this process affects large areas (Houghton et al. 1985), and accounts for a significant proportion of total greenhouse emissions: 26% for carbon dioxide, 48% for methane and 33% for nitrous oxide has been estimated from deforestation processes (Houghton 2005). The relation between fire and deforestation in developing countries, both including complete clearing and selective logging, has been well documented (Cochrane et al.1999; Skole and Tucker 1993; Souza et al. 2005).

For industrialized societies, the opposite trend to deforestation has been observed in the last years, since socio-economic changes have implied a growing migration from rural areas to cities and, as a result, an increase in land abandonment and regeneration of tree cover (Leone et al. 2003). Parallel to this trend, in developed countries is the increasing use of forested or woodland areas by urban populations for recreational use. In many cases, these recreational activities may cause fires either by carelessness or arson, associated to hunting practices, land use regulations or conflicts with natural protected areas (FAO 2007; Martínez et al. 2009).

The effects of fire can be analyzed at different spatial and temporal scales. At global scale, one of the most critical impacts of fire is gas emissions released by biomass consumption, which alters atmospheric chemistry. Worldwide, it is estimated that total gas emissions from biomass burning are about 4.5 Pg C year$^{-1}$ (Levine 1996). This amount is more than half the total emissions due to fossil fuel combustion, which averages 7.2 Pg C year$^{-1}$ in the 2000–2004 period, according to the IPCC (2007). More recent estimations of fire emissions account for 3.5 Pg C year$^{-1}$, or roughly 40% of total fossil fuel carbon emissions (van der Werf et al. 2004). However, a wide uncertainty in these estimations is generally acknowledged (Palacios-Orueta et al. 2005; Randerson et al. 2005; van der Werf et al. 2006).

At a more local scale, fires also affect vegetation succession, soil erosion, hydrological cycle and have impacts on human lives and properties. In forested areas, fire aids in stand thinning, the clearing of understory vegetation, and promotes vertical stratification of the forest canopy. For instance in semi-arid regions where natural decomposition rates are very slow, fire is a critical process for recycling dead biomass (Running 2006). Soil alteration as a result of fire depends on fire intensity and residence time. Low intense fires help the mineralization of vegetation and provide N and other nutrients to the soil, while intense fires may destroy microbiological organisms and increase erosion after heavy rains (Nearya et al. 1999). Changes in hydrological regulation as a result of vegetation removal from fires are well documented (Doerr et al. 2006; Francis and Thornes 1990).

Finally, fires have also important impacts on human lives and resources. Data on human losses are not systematically collected worldwide. Following the previously quoted report from FAO (2007), only a few countries quoted figures on fire damage (107 million US$ of annual losses in India, 337 million US$ in Mexico and 4,200

million US$ in Russia, for instance). Direct losses of human lives from fires have been reported from single events. In the fall season of 1983, 75 people died as a result of fires in Australia and more than 2,500 houses were lost. More than 100 people died in West Africa as a result of catastrophic fires of 1982–1983 and the Dragon Fire in China causes in 1987 the death of 221 people and the burning of 50,000 houses. The 2007 fires in Greece caused the death of 84 people and the destruction of more than 1,000 houses in the Southern part of the country. Recent fires in Australia have burned thousands of houses and have killed more than 180 people in the first estimations.

Fires have also important effects on human health as a result of smoke pollution, ashes and particulate matter produced by the combustion process. Very critical situations occurred in Malaysia and Indonesia during the fires following the strong El Niño drought of 1997, where smoke caused the closing of several international airports and some cities were evacuated. More recently, dense smoke caused by intense fires in Paraguay and Argentina, caused several car accidents and respiratory problems for the population of Asunción and Buenos Aires. Health impacts associated with fire are more critical for people with respiratory problems, hearth diseases and children. In several regions of the World (e.g. South Asia) agricultural burning of crop residue during the dry season contributes with other sources of aerosols to produce chronic air quality problems.

## 1.3 Fire Regimes

The effects of fire on society, vegetation, soil and the atmosphere are strongly associated with fire characteristics (density, frequency, severity, intensity, seasonality, size distribution, etc.). Fire is beneficial for vegetation and soils when it is well adapted to natural conditions, but it is harmful when natural cycles are shortened or fire conditions are more severe. For this reason, the analysis of current fire conditions are very important to understand the potential effects of fires, as well as to foresee future scenarios of fire impacts as a result of climate or socio-economic changes.

Fire should not be considered a binary phenomenon (burned/unburned), but rather a dynamic process that requires further knowledge on the interactions of fire and the environment, which are closely associated to where, when and how the fires occur in a particular area. Within this approach, the term fire regime is commonly used (Chuvieco et al. 2008b; Morgan et al. 2001; Stocks et al. 2003). Fire regimes refer to the average conditions of fire within a particular area occurring over a long period of time. These characteristics relate to the density of fires (number of fires within a given area), fire size (average extent of burn patches), fire frequency (return interval in years) or fire recurrence (how regular the fires occur in a particular region), fire intensity (measured in units of energy for burning area), fire duration (residence time, in hours or days), fire seasonality (when fires occur during the year and how long the fire season lasts in months), and fire severity (social or ecological impacts of fire, which are commonly associated to fire intensity and duration).

All these characteristics explain whether the impacts of fire on vegetation and soil are beneficial or detrimental. Fire severity impacts soil degradation and vegetation consumption, which in turn affect regeneration patterns and biomass emissions. Fire size accounts for the global impact of fire on landscape pattern, whether fires are frequent and small or sporadic and large, creating different spatial mosaics. Fire seasonality, along with severity, is closely related to weather conditions and vegetation fire resistance (protection capacity against fire) and resilience (capacity to recuperate from fires). Whether fire occurs under dry or moist conditions will have a great impact on vegetation succession and recovery, as well as on soil erosion and the hydrological cycle.

Historical changes in fire regimes have been approached from proxy data (such as tree rings or sedimentary records), since fire statistics are usually only available for a short periods of time, wherever they exist. From proxy data, long-term trends of fire regimes may be build, analyzing the relations between fire occurrence and climate fluctuations (Batek et al. 1999; Bergeron et al. 2004; Vannière et al. 2008). However these analyses are usually local and difficult to make spatial extrapolations.

Recent availability of global fire data derived from satellite images has been used to approach global fire regimes, either using detected active fires or burned areas. Several authors have analyzed global fire regimes from NOAA-AVHRR or Terra-MODIS data (Carmona-Moreno et al. 2005; Csiszar et al. 2005; Chuvieco et al. 2008b; Dwyer et al. 2000; Riaño et al. 2007b). The former provide a longer time series, while the latter are more precise measurements of both active fire and burned area (Chuvieco 2008). Although these studies are based on short periods of time, they provide a first approach to characterizing groups of fire conditions worldwide (Fig. 1.3). Those fire groups are associated with climatic and socio-economic condi-

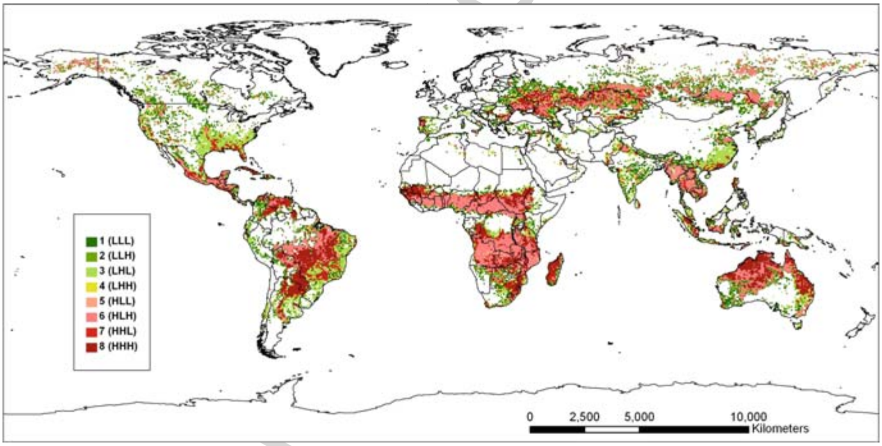


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**Fig. 1.3** Classification of fire regimes. H refers to high values and L to Low values and the order of columns accounts for Fire Density, Duration and Variability, respectively (adapted from Chuvieco 2008 #5016)*

*For colour version of this figure, please refer Colour Plate Section.

tions (Chuvieco et al. 2008b), and express the different adaptations of human activities to the use of fire use.

## 1.4 Factors Controlling Fire Regimes

Fire regimes have been historically driven by climate cycles, being more frequent in drier-warmer conditions. Recent studies based on sedimentary charcoal records in central Italy evidence the presence of high-frequency fire phases, lasting 300–500 years, associated to dry summer seasons during the Holocene (Vannière et al. 2008). Similar patterns of climate cycles and fire occurrence have been observed in the Idaho-Montana region, where tree ring records and sedimentary analysis showed the relation between cold periods and the occurrence of low-severity fires, while the existence of warmer periods implied more intense, typically stand-replacing fires (Pierce et al. 2004).

The strong climatic control of fire activity has been transformed in the last centuries by the growing use of fire by humans, thus altering natural fire regimes in most ecosystems. One of the most interesting topics of fire-related research is the analysis of the ecological impacts of current fire regimes and the potential impacts of future climate and socio-economic conditions. To achieve this we need to assess whether current conditions are different from historical observations, identify the factors of change and better understand relations between current fire regimes and ecological processes (Fig. 1.4).

The analysis of changes in fire regimes requires a consistent record of fire observations, which provides a solid assessment on whether fire regimes are changing or not. The more extended databases come from the seventies, although for specific regions a longer statistical series may be available. A good example is the Canadian large fire database (Stocks et al. 2003), which extends from 1959 to 1999, covering all fires in the country larger than 200 ha. Several studies have been based on this database, which provides a good spatial and temporal view of fire patterns in Canada (Gillett et al. 2004; Parisien et al. 2006; Skinner et al. 2006). Using Canadian and US statistics, several authors have shown a recent increase in fire activity and severity,

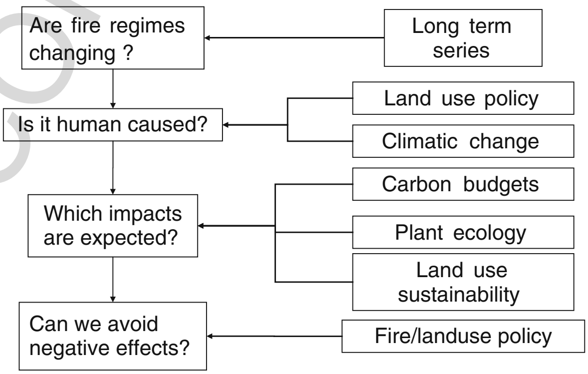


**Fig. 1.4** Framework for investigating potential changes in fire regimes

especially in the boreal regions (Kasischke and Turetsky 2006; Skinner et al. 2006; Westerling et al. 2006).

However, fire historical databases are not necessarily compatible throughout the time, because of data gathering errors or inconsistencies in data collection, and therefore the temporal series may not be very reliable (Brown et al. 2002). Remote sensing may provide an alternative means to build historical time series of burned area or active fires, since the observations are compatible through time, but these series are limited to the last 25 years, from NOAA-AVHRR or Landsat-TM/ETM+ images (Chuvieco et al. 2008a; Pu et al. 2007; Riaño et al. 2007b).

Once recent changes in traditional fire regimes are proven, a second line of fire research relates to identify and explain the main factors controlling those changes, as well as to assess what potential impacts those changes will have, in order to introduce correction measures. It is commonly assumed that traditional fire regimes implied somehow equilibrium conditions, and recent changes caused by socio-economic factors disturb that equilibrium and therefore have negative impacts on natural ecosystems (Pyne 2004).

Several major causes are responsible for changing fire regimes, but they can be grouped in two main categories: climate and human driven. The former relates to the impact of climate cycles on fire activity, which have been historically observed from sediment records or tree-ring analysis. The latter includes the impacts of land use policy and socio-economic transformations.

The impact of last decades' climate warming on fire activity has been recently emphasised by several authors (Gillett et al. 2004; Running 2006; Westerling et al. 2006). The most important effects of climate change are the extension of fire seasons, by earlier snowmelts and longer summers, which tend to be warmer and drier. Similarly changing rainfall and temperature regimes may alter the amount of fuel available for burning or the condition of the fuel. In a recent study, Westerling et al (2006) found that the length of the active wildfire season in the western United States between 1970 and 2003 has increased by 78 days, and that the average burn duration of large fires has increased from 7.5 to 37.1 days. They attributed this increase in wildfire activity to an increase in spring and summer temperatures by $\sim$0.9°C and a 1- to 4- week earlier melting of mountain snowpacks. They also found that those years with earlier snowmelts had as many as five times more wildfires that those with late snowmelts. Other authors have observed similar trends in the boreal forest of North America (Kasischke and Turetsky 2006; Stocks et al. 2003). Close relationship between sea surface temperatures and fire occurrence and severity in Canada has been observed (Skinner et al. 2006). The authors found several couple modes variability between the seasonal severity rating (SSR) index and the previous winter global Sea Surface Temperature (SST). The explanation modes of fire activity are based on three climatic cycles: long-term trends in the Southern Hemisphere oceans, to the multidecadal variation of Atlantic SST and to the Pacific Ocean processes and the interrelationship between El Nino-Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO).

As regards human factors controlling fire regimes, two almost opposite trends can be distinguished, depending on the importance of the agricultural sector in the

regional economy. In developed countries, the recent transformation of rural areas, as a result of massive migration to the cities and the industrialization process, has implied a vast process of land abandonment and interruption of traditional practices in rural areas, such as grazing, energy consumption from wood, or extensive grazing (Leone et al. 2003). These changes have also resulted in a larger accumulation of fuels, which increase fire intensity and severity compared to natural conditions, altering landscape structure that was historically shaped by less severe fires (Vega-Garcia and Chuvieco 2006).

Another factor affecting changes in fire regimes in developed countries is the impact of fire-exclusion policies (Houghton et al. 2000; Pyne 2001). The suppression of all fires in forested areas, as a result of an aggressive policy towards fire has implied an anomalous accumulation of fuel, which would have been reduced if natural fires were allowed to occur. Consequently, when fires actually arise, they have more severe effects than in natural conditions, thus implying more negative impacts on plants and soils. Following this explanation, by avoiding small-natural fires with potentially positive effects, fire managers are indirectly causing larger and more severe fires, which are those occurring under extreme weather conditions and are almost impossible to control. In a very interesting paper, Minnich (1983) compared fire patterns between US and the Mexican Southern California region. The former, with intense fire suppression activities, and the latter with very little or no fire suppression. The total area burned in the historical series analyzed by Minnich is similar in both areas, but with very different spatial patterns: few and large fires in the US territory, while many and small fires in the Mexican area.

Social conditions related to fire occurrence are very different in developing countries. Land use trends in those areas still favour the agricultural expansion over forested areas, and therefore the use of fire as an inexpensive tool of land clearing. This tendency occurs mainly in tropical countries, which are widely affected by deforestation and selective logging (Cochrane et al.1999; DeFries et al. 2002; Souza et al. 2005). Most of these forests are not well adapted to fire, and even though the fires are commonly shallow, they have intense impacts on local vegetation. The boreal forests of Siberia have also shown impacts of deforestation and agricultural expansion, which are commonly associated to intentional fires (Mollicone et al. 2006).

In summary, most authors recognize that humans play an integral role in most of the Worlds fire regimes. Perhaps, only in the remote and unmanaged landscapes of the boreal zones of North America can the human role be considered negligible (Johnson et al. 2001).

## 1.5 Fire and Climate Change

Fire is not only affecting global processes of atmospheric chemistry and land use transformation, but it is also affected by those processes, as changes in factors controlling fire regimes imply modifications of fire occurrence patterns. Within this

scope, interesting research topics arise from considering future scenarios of climatic or socio-economic conditions in particular areas, to better understand potential changes and mitigate the more negative impacts of the predicted fire regimes on ecosystems and society.

Future scenarios of climate change should affect locally fire regimes, and therefore local analyses need to be performed by adapting global climatic models to regional conditions.

The boreal region of the Northern hemisphere will be particularly affected by climate change conditions, with warmer and drier summers and longer snow-free seasons. This trend would result in longer fire seasons, shortened fire cycles and reductions of carbon stocks. An assessment of different scenarios derived from Global Climatic Models (GCM) has estimated that burn areas in Canada are expected to increase by 74–118% at the end of this century (Flannigan et al. 2005).

Other authors have hypothesised that carbon lost may be balanced by increasing net primary production (NPP) as a result of warmer temperatures. Several authors have discussed the importance of both trends from future climate scenarios and carbon budget models. They found that significant increases in net ecosystem production would be required to balance carbon losses from increased natural disturbance rates, and therefore carbon stocks in boreal forest are expected to decline as a result of climate change (Kurz et al. 2007). In case this trend is confirmed, it would have positive feedbacks on global climate warming, since a very important terrestrial carbon sink may become a net source. In fact, some authors have pointed out that mid and high-latitude ecosystems in the Northern Hemisphere are responsible for the largest proportion of the net terrestrial carbon sink (Goodale et al. 2002).

Future changes in Mediterranean climatic conditions have been assessed by GCMs, but further efforts are required to better understand local implications of climate change. Since the vegetation is well adapted to summer droughts, it would be probably less affected by severe changes in fire regimes than other ecosystems, but extended and more fire seasons are expected (Moreno 2005).

## 1.6 Conclusions

Fire is a global process with a wide variety of factors and effects that need to be further researched to better understand potential implications of future climate and socio-economic changes. Fire needs to be considered as a complex phenomenon, characterized by different variables, most properly through the concept of fire regimes, which includes fire density, size, persistency, seasonality, causality, intensity and severity. Satellite data along with other sources of spatial and temporal information provide critical sources of data to assess trends in fire regimes and characterize their potential impacts.

# Chapter 2
# Eternal Flame: An Introduction to the Fire History of the Mediterranean

**Stephen J. Pyne**

> . . . *And thus he speaks*
> *And in his hands bears forth from inmost shrine*
> *The Fillets that betoken Vesta's power,*
> *And her undying fire.*
> – *Vergil,* The Aeneid*, Book II*
> *Fire, as is well known, seeks a void toward which and in which*
> *it can move.*
> – *Theophrastus,* De Igne

**Abstract** The physical geography of the Mediterranean renders it an ideal landscape for burning. But for thousands of years its fire regimes have been set directly and indirectly by humans. Because of the region's significance in Antiquity, it has been studied for a long time and has become for good or ill a paradigm for thinking about fire. In this regard the Mediterranean has been both a place to export ideas and a place to received them. Today's thinking about the Mediterranean and fire is thus as complex as its intricate landscapes. But the fundamental reality remains, as first voiced by Theophrastus: fire is tame or feral as humans contain or unleash it, which they do not only by the torch but by close tending of the landscape.

## 2.1 De Igne

The landscapes of the Mediterranean burn. They have burned as long as people have recorded history, and they have continued to burn through wars, famines, droughts, floods, eruptions, epidemics, the advent of farming and livestock, and that wrenching upheaval in social order, economics, and fire practices known as industrialization. Today some 90% of the burned area of Europe resides within the

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Mediterranean. Among the landscapes of Earth, the Mediterranean is a kind of prytaneum, the hearth for an eternal flame (Frazer 1995).

The Mediterranean is a place, a climate, a biota, and a paradigm. Its physical geography makes it practically a dictionary definition of a fire-prone environment. Its climatic pattern of annual wetting and drying, overlain by episodic drought ensures that there is always something to burn. The mountains that act as geographic spokes and rims create a kaleidoscope of niches that simultaneously provide points of ignition and baffles against spread. Its fabled winds – the mistral, the bora, the sirocco – can fan small flames into huge. An ancient, relentless drumbeat of disturbances has selected for a fire-tempered biota, for even where fire is not itself a dominant presence, it catalyzes and accompanies almost every other stress. What the region lacks is a routine source of kindling. Outside its high mountain fringe, the arc from the Pyrenees through the Alps to the Olympics, lightning is sporadic, even rare (McNeill 1992; Pyne 1997).

Its natural history, however, is not what has identified the Mediterranean universally with fire. That honor belongs to its human history. The Mediterranean is an utterly anthropogenic landscape. Its fire-sculpted biota is an artifact of human-wrought disturbances. For millennia people have determined the sizes, shapes, and arrangements of the biotic tiles that make up the landscape mosaic; they have set the tempo and rhythms for burning; they have established fire's regimes. For 10,000 years in its eastern lands and 4,000 years in its western, the natural history of the Mediterranean has been barely distinguishable from its social history. Together nature and culture have ensured that the Mediterranean endures as a *flamma aeterna*.

## 2.2 *Ager et Silva*: Fire in the Garden

The flora is rich, its history dense. Here, where Africa, Europe, and Asia meet, where violent fluctuations in climate have pumped in and flushed out species like a bellows, where many cultigens have originated and others have gathered, where civilizations have long flourished and decayed, where land use has alternated between warfare and gardening, the biota has proliferated, toughened, degraded, and endured.

Its diversity results as much because of that history as despite it. The typical Mediterranean biota is hardened against stresses of all kinds; drought, poor soils, browsing, and cutting, no less than fire. The flora is as durable as marble, as friable as limestone. It is protean, malleable, hard-used. Here, not surprisingly, the term "pyrophyte" originated. Its inventor observed that the Mediterranean biota was heavily pyrophytic, and in many regions, like his native Provence, almost wholly so. The maquis, in particular, distilled the pyric essence of the biota: it was the Mediterranean biota in miniature, capable of being compressed or released as pressures mounted or faded (Trabaud 1987).

Whatever the "natural" biota might be, the singular fact of its Holocene history is that it has been selected, arranged, and burned according to human wishes. A domesticated biota has long replaced a wild one; in fact, "wild" might be better

characterized in such circumstances as “feral,” which is to say, the domesticated shorn of its cultivators and leashes. In its raw state the biota can morph into many forms; and this is as true for the landscape as for its more robust species. Pushed one way, it tends toward shrubs; another way, to woods; yet another, to grasses and forbs. But whether farmed, grazed, logged, or cleared, it has been burned. The outcome is an environmental palimpsest, a biotic cognate to those ancient parchments rudely (and incompletely) erased and written over again. For the landscape fire often serves as both scraper and stylus, and it literally brands a chronicle of human occupancy onto the region.

By the time of the classic agronomists, the Mediterranean landscape had three basic parts, each one of which targeted for domestication a distinctive component of the biota (grass, shrub, or tree). The *ager* was the cultivated field. The *saltus* was the rough pasture. The silva was the woods, or in a still more domesticated variant, the orchard. The cultivation of the first yielded agriculture, and of the latter, silviculture (or arboriculture). The cultivation of the olive tree often serves as a working definition of the Mediterranean culture region. The cultivation of fruiting shrubs inspired viticulture. But it was the pasture that could never be yoked completely to the plow or the pruning hook. The Mediterranean fauna had an unfetterable mobility that its flora lacked (Kuhnholtz-Lordat 1958).

This arrangement displayed both geographic and seasonal preferences. The fields occupied the valleys, and where population pressures were intense, they sprawled up terraced hillsides. The flocks and herds migrated from summer to winter between valley and mountain pastures. They could supplement that natural fodder where the *ager* lay in a state of fallow, for there they could gather to feed and fertilize. At almost every site and every practice, somewhere, at some time, fire entered. But it was amid the mountain *saltus* that fire burned most widely, with the untrammeled mobility of the flocks, and in those remote regions as yet unyoked from even human herders.

Here free-burning wildfire might rage, as it did in Homeric similes: “Through deep glens rageth fierce fire on some parched mountain side and the deep forest beneath, and the wind, driving it, whirleth everywhere the flame.” The Pyrenees received their name from their frequent fires; one, reportedly in 200 BC, fixed itself vividly in the imagination of the time. But already by Periclean times, Thucydides knew such heroic wildfires only as literary tropes, an allusion from “times past in the mountains.” When Vergil likened the rush of Aeneas and Turnus to “fires lighted all about to burn/ A parching wood and rustling brakes of bay,” he spoke in epic simile. When Lucretius imagined a “fierce conflagration, roaring balefully” that has “devoured a forest down to the roots,” he was speaking hypothetically; the putative melting of rock, not the dynamics of the fire, commanded his interest. But such landscapes became rare, as humanity and its servant species absorbed or remade them and brought them under the domesticating hand of agriculture (Semple 1931; Thirgood 1981; Liacos 1973; Lucretius 1951).

This organization of the landscape to satisfy agriculture determined the larger dynamics of fire. People imposed an order, much as they built roads and turned hillsides into amphitheaters. Their resort to fire was not simply opportunistic or

slovenly: fire was an implement of domestication as fully as crock or scythe. It was herded, plowed, hoed, and harvested according to a calendar of cultivation. Even more, it was a universal catalyst that made other technologies work.

The patches of field and fallow traced the units of fire behavior; the cadences of sowing and fallowing dictated the rhythms of burning. Viewed another way, the whole enterprise was an expression of applied fire ecology. People were not simply tending the landscape as a means of controlling wild fire (outside the conifered mountains, there was little natural fire). Rather, they brought fire to an environment that could absorb it within a general suite of disturbances; they applied it for the fumigating and fertilizing effects it produced. They burned the land for the same reasons celebrated in their fire ceremonies, because fire promoted the good and purged the bad (Frazer 1923).

But to have fire, you need fuel, and in an agricultural system, this means cultivating combustibles as fully as other products. That was the purpose of fallowing. It ensured fuel would be present so that fire could adequately rekindle the site, and it defined the bounds of such burning. Even in classical times, agronomists raged against the practice, which they saw as wasteful, superstitious, and dangerous. But they misread its purpose, its role as a fire practice. The point was not to burn the fallow as you might garbage, but to grow fallow so that it might be burned. Almost alone did Vergil in his *Georgics* sing the praises of the burning field.

What joined all the parts into a coherent whole, or in pyric terms, what made the Mediterranean a fire domain, was the presence of the human hand and head. The anthropogenic landscapes of the Mediterranean favored pyrophytes as ancient sculptors favored marble. The actual composition and shapes of the Mediterranean mosaic were no more a product of lightning and wind than the temple at Delphi was the outcome of natural erosion. Everywhere human artifice dominated, and because human technology relied on fire, the biomes that resulted favored species that could endure fire or that flourished best under a regimen of regular fire.

When people were removed, a revanchist biota could blossom into a great stew of species that might require centuries to sort itself out. That happened on scales immense and minute as population swelled and collapsed, as famine, war, plague, and economic distress put land into and out of active cultivation. Once terraced hillsides might overgrow with shrubs; fields might blossom with weeds; orchards could crumble into tangles of branches and brush. What was farmed might be browsed, the saltus might be converted into ager, the silva might become saltus. To the climatic cadences of annual aridity and decadal drought were thus added the stochastic rhythms of business cycles and geopolitical movements. Bad behavior expressed itself as landscape: tyranny over one manifest as an oppressive tyranny over the other. The Fall of Rome acquired an environmental gloss that tracked equally the disintegration of an ecological order. Mediterranean fire began its career as a parable of human stewardship.

The cycle of fire came into alignment with the cycle of empires. In George Perkins Marsh's classic rendition, "The decay of these once flourishing countries is partly due, no doubt, to that class of geological causes, whose action we can neither resist nor guide, and partly also to the direct violence of hostile human force;

but it is, in far greater proportion, either the result of man's ignorant disregard of the laws of nature, or an incidental consequence of war, and of civil and ecclesiastical tyranny and misrule." The rot that became the later Roman Empire had an environmental expression, not simply as a simile but because the human hand made it happen. Thus, in Marsh's formulation, Rome overtaxed agriculture, which overstressed production; so conscripted labor for public works and military duty that the countryside went untended; ruined commerce, redirecting efforts away from use to extravagance. "Hence, large tracts of land were left uncultivated, or altogether deserted, and exposed to all the destructive forces which act with such energy on the surface of the earth when it is deprived of those protections by which nature originally guarded it, and for which, in well-ordered husbandry, human ingenuity has contrived more or less efficient substitutes." Oppressed societies created oppressed landscapes. Ruinous fires resulted from ruined places (Marsh 1865).

Over millennia, the Mediterranean became a vast Garden, or a patchwork quilt of gardened sites stitched together by related cultivations. Directly or indirectly, almost nothing remained outside this matrix. What was not ager was saltus or silva. What was not farmed was grazed, tapped for resin, harvested for wood, foraged for mast, fed into flocks. Sometimes the parts were separated by either geography or season, stitched to a common fabric by long threads of migrating livestock. Sometime they overlaid, so that farmers intercultivated cereals with olive groves, or grazed herds on stubble. No place was truly wild. And no place was wholly spared fire.

Fire appeared with every patch, with every interstitial wildland in chrysalis from one state to another. For the agriculturalists the torch was an implement of gardening like ax, plow, and rake. It broke new ground, recycled nutrients in fallow, removed waste, and fueled forge and hearth. Fire and ax readied sites for shifting cultivation, and then prepared them for the rotations of sedentary farming. Fire assisted the harvest of olives and chestnuts by clearing the ground of debris. Farmers burned old and diseased branches, overgrown ditches and canals, and agricultural residue as part of an annual cycle of cleaning. Fire cleared away overgrown thickets, pruned vines, and disposed of briars, tares, and stubble (Steensberg 1993).

Fire was present because people were, and people could inhabit the land because they could burn it. The Mediterranean was a manifestation of a pyric symbiosis between humanity and nature.

## 2.3 *Saltus et Transhumancia*: Fire and Flock

Of course the system did not always work as proposed by theory; and there was one component that could never be made to work even in principle. This was pastoralism. Small-scale husbandry – the milch cow or goat, the draft ox, the beast-of-burden donkey – these were working pets, amenable to integration into the close-cultivated landscape. Herds of swine or cattle, flocks of sheep and goats, that trekked between lowland and mountain pastures according to the rituals of *trashumancia*, could not. Transhumance decoupled flock from field. Transhumance was an

ecological circle that agronomy could never square (Semple 1931; Rafiullah 1966; Ruiz and Ruiz 1987; Le Houerou 1981; Kish 1954; Evans 1940).

Pastoral burning claimed the largest fraction of landscape burning, and it dominated the imagination of critics. The incendiary shepherd, promiscuous with fire, antisocial in behavior, became a stock figure in Mediterranean literature, sometimes celebrated in the pastorals of lyric poetry but more often denounced by intellectuals, farmers, and outsiders. He was the model for the satyr, the anarchic Pan, or the cloven-hoofed Satan. Amid a landscape dedicated to a gardened rigor, with every plant (and every person) in its appropriate place, he moved, and his flocks often trampled the fixity of the social order. So did his fires. Tradition and law sought to channel both flock and flame into regular routes and rhythms – the *calles publicae* of Rome, the *tratturi* of Italy, the *carraires* and drayes of France, the *cañadas* of Spain. Where close shepherding was possible, they succeeded, and where such tending was not, it failed.

Transhumance assumed several forms, and as typical for the Mediterranean, they varied not only by geographic features but social arrangements and especially politics. In its basic version transhumance bound villages to local mountains. Up the slopes the flocks went during the spring, and down they came in the fall. Where the central state was weak and the terrain rugged, transhumance never organized further. This was the case, for example, with autarkic Greece whose free-ranging goats seemed to critics to trample about the countryside like banditti. At the other extreme, Iberia combined a vast interior plateau (the *meseta*), the centuries-long history of the *Reconquista*, and eventually a powerful state to fashion a far-droving monopoly, the famous *Mesta*. The outcome was a seasonal pattern of almost migratory transhumance across the *Meseta*; these patterns had developed as an outgrowth of the seasonal fighting characteristic of the *Reconquista*. The flocks and herds accompanied the armies that advanced and retreated, laying down over the centuries great routes of annual movement, an ecological counterpart to Roman roads. As the advanced pushed further, so the routes lengthened until they virtually crossed the plateau. By the 13th century the monarchy began organizing the sheep migration by granting a chartered monopoly, El *Honrado Concejo de la Mesta de Pastores*, which guaranteed revenue to the state. The *Mesta* evolved into a dominant institution and a major ecological presence that helped also to organize the lines and fields of Iberian fire. As befit its intermediate geographic status, Italy offered a mix of both models, including a Mesta-equivalent, the Dogana, installed when Alfonso V of Aragon ruled chunks of the peninsula (Kish 1954; Klein 1920).

The pastoralists burned, notably in the fall, ahead of the winter rains, and their fires often sprawled over landscapes as indifferently as the flocks. Most allusions to fire in classical literature refer to just such blazes. Silius Italicus thus described the “multitude of fire that the shepherd see from his seat on Mount Gargano (Apulia) when the grazing lands of Calabona are burned and blackened to improve the pasture.” In the *Aeneid* Vergil turned such practices into epic simile:

> . . . when summer winds are risen
> In answer to his wish, at points apart
> The shepherd launches fires against the woods;

And on a sudden, the mid spaces caught,
Vulcan's grim line now spreads unbrokenly
Across the stretching plain; he from high seat
victorious views the triumphs of the flames (Pounds 1973; Vergil 1961).

The combination of burning and browsing shaped the indigenous biota into a spectacular shrub land. The generic maquis was a marvelously supple biome, dominated by pyrophytes; it was the indigenous flora boiled by pastoral burning into a biotic sap, and occasionally into a near-crystalline solid; it was the Mediterranean biota in miniature, capable of being compressed or released as pressures permitted. Some of those pressures resided in the peculiar terrain and weather of the region; some was coded into its hard-edged evolutionary ecology; and some – the fraction that was most responsive – was held in the fussy hands of humanity.

## 2.4 *Mediocritas* and Mediterreaneity

It was "well known," Theophrastus had asserted, that fire would "seek a void toward which and in which it can move." Untended, abandoned, overgrown sites were just such landscape voids; they would draw fire like air sucking into a vacuum. But under typical conditions there were few such vacuums. Instead intensive cultivation kept the scene clear. Debris was burned as trash, the land was fired in patches, the patches were kindled at different times. In principle, no one part of the tripartite division of the landscape would dominate the others. Society would remain orderly, its lands gardened and its fires tended. And in places it might be possible to abolish fire altogether by promoting biological or social surrogates (Theophrastus 1971).

But principle was never practice. The Mediterranean is not an environment best characterized by means, or the *mediocritas* beloved of ancient philosophers, but by nonlinearity and extremes, what has come to be called Mediterraneity. The temperate ideal was an even cadence: seasons varied by temperature, not by precipitation, and while precipitation might vary by type with seasons, it fell more or less constantly month by month, year by year. So was its agricultural landscape bound part by part, a cycle of herding, cropping, and manuring. In the Mediterranean, however, the defining processes came in bunches, the big and exceptional event had greater impact than many small ones, and the pieces never interlocked with the careful intricacy of temperate lands. The valences were looser, which is exactly what a landscape prone to sudden and extreme events needs if it is to recover (Kunholtz-Lordat 1938).

So, too, its human history has not been one of tempered evolution but of cadences of order and breakdown, not unlike the cosmological cycles conceived by the Stoics, each concluding with its world-reshaping Great Fire. Plagues, wars, droughts, famines, migrations, high winds – all kept the basin aboil. Sometimes pastoralism would dominate, sometimes farming, sometimes vines and olives. The extraordinary capacity of the landscape to support a mosaic of domesticated flora and fauna ensured that something was always available to fill the voids; but it was exactly

during those transitions from one state to another that Theophrastus' prophesy of fire filling the vacuums proved true.

## 2.5 Colonization north: from *Mare Nostrum* to *Europa*

Mediterranean agriculture spread north, first piecemeal through the Neolithic revolution that carried small-scale swidden and livestock into temperate Europe, and then, more formally, through the expansion of the Roman empire and its successor states through medieval Christendom.

Passage beyond the Mediterranean's mountain fringe, however, involved two transformations. First, it meant that cultigens forged in a Mediterranean climate of winter rains and summer drought had to adapt to a climate of summer rains, and of more or less constant precipitation (of some form) throughout the year. This demanded site preparation; specifically, it meant that the catalytic effects of fire required that landscapes not naturally prone to burning were put into a condition to burn. Slashing, browsing, and draining in patches accomplished this. Swidden cultivation fashioned microenvironments that permitted the exotic cultigens to thrive.

Second, the colonization north brought a change in how domesticated flora and fauna interacted. Transhumance persisted, particularly in mountainous regions like the Alps, Carpathians, and Nordic ranges (and in peculiar forms such as reindeer herding in the far north); but harsh winters forced livestock into barns, where they accumulated manure that was subsequently delivered to arable fields. In various ways pastoralism and farming forged a valence that defined a peculiar style of agronomy, one celebrated by academics and political ministers through the scientific revolution and its agricultural successor. It asserted that burning was a stigma of primitivism, and that manure and close cultivation might abolish the need for burning altogether.

This mattered particularly once central, or temperate, Europe became the defining core of Europa. The 8th-century Arab conquests sundered the northern Mediterranean rim from its southern; in fact, save for small enclaves like Venice, Europe ceased to have any direct contact with the Mediterranean. As Europe recovered, as it began various forms of reconquest and crusade over the next few centuries, it did so from a temperate interior; and beyond the northern fringe of Rome's mare nostrum and Iberia it never succeeded in reclaiming the old Roman imperium, as new waves of aggressive Moslems, notably the Turks, replaced the Arabs. The ancient link to an intrinsically fire-prone landscape broke. Instead, the European ideal became the cultivated landscape of central Europa. And as theorist after theorist insisted, this was a landscape for which fire did not intrinsically belong and from which it should be abolished (Pirenne 1939).

In truth, fire was all over central Europe: it was as much a part of agriculture as plows, and in many respects, more indispensable. But its use was ever-condemned by officials, academics, and an emergent profession, forestry. A spectacular illustration occurred in 1752 when Linnaeus, then at the height of his fame, was forced

to delete some passages favorable to burning from his royally sponsored travelogue to Skåne. Baron Hårleman, the minister of agriculture, demanded instead that Sweden's most renown naturalist insert a long text that celebrated manure. The central European Garden had no place for fire except in the hearth and forge (Weimarck 1968).

The obverse observation also came into vogue: the Mediterranean, rather than being an agricultural paradigm, was a backwater. Unable to reconcile its flocks with its fields, incapable of boosting output with manure or special breeding, unwilling to shut down fires, it lay outside the dominion of scientific agronomy and a capitalist economy, a relict from the past, as burdened with tradition and superstition as religious icons and no more capable of addressing contemporary needs than the aphorisms of Heracleitus the Dark. The Mediterranean's was a legacy landscape from Antiquity, as quaint as the physics of Aristotle. When, by the 18th century, temperate Europe became a global center for learning, industry, and imperial enthusiasms, its ideals prevailed, its norms got written into global institutions like forestry, and its values were disseminated around the world.

## 2.6 Colonization West: An Exchange of Fire

Before then, Mediterranean fire shipped westward with the Great Voyages. The Age of Discovery was overwhelmingly an Iberian project. The fire that Spain and Portugal exported across the world ocean was Mediterranean in its practices and its associations with introduced flora and fauna.

Fires were a means of contact, marking both points of departure and arrival. Columbus noted a beacon-like "great fire" on Tenerife as he sailed west from the Canaries, and that dark evening before landfall in the Bahamas, the seamen of the *Niña* noted a candle-like flame that beckoned them on. His ships of course carried fire in their holds; their fires met and engaged with the fires of indigenes. The discovered New Worlds became places that would involve an exchange of fire (Cohen 1969).

This was a vastly more complex process than the Neolithic settlement northward through Europe and its subsequent reorganization under the norms of Antiquity. In the discovered lands almost every place that could hold fire did, often within an agricultural matrix. What European *conquistadores* and *colonos* did was to upend the indigenous order, add livestock to that mix, and reconstitute the landscape under a regime of *mestizo* burning. The transplant was especially vigorous where the transfer was from one Mediterranean climate to another; these became hugely successful colonies, or to adapt Alfred Crosby's language, Neo-Mediterraneans (Crosby 1986).

Some unique practices and institutions, however, were transplanted, particularly those connected with herding for which the indigenous societies had no prior experience since, outside Peru, they lacked domesticated herds. Thus New Spain, which introduced plagues that depopulated immense landscapes of indigenes and put their fields to fallow, reclaimed those sites as pastures for sheep, horses, cattle, swine, goats, and donkeys, and even organized the Mexican altiplano along the lines of

the Spanish meseta, complete with a Mexican mesta. That tradition of long-distance droving pushed north, regrouping in south Texas before eventually extending over the Great Plains. Open-range herding dominated much of the piney woods of the American South. Semi-feral cattle claimed the Argentinean pampas, the llanos of Venezuela, and the cerrados of Brazil. Sheep and goats tramped over the Andes. Loosed goats remade islands from Santa Catalina to Juan Fernandez (Crosby 1986; Melville 1992).

Later, Basque shepherds brought their fire practices to the mountains of the American West, where their smokes flooded valleys and socked in summits (and where they became an object of fury to early conservationists like John Muir, for example, who raged not only against the "hooved locusts" but the landscape-trampling fires set by their nominal tenders as well). Foresters, in particular, viewed herders as their ancestral rivals, and saw burning to promote browse as a senseless transfer of bad habits from a landscape such practices had, to their minds, already trashed (the Mediterranean) to a place fresh with promise. Their ancient quarrel would extend into America as it did through the lands Europe colonized.

## 2.7 Colonization South: Imperial Forestry

Eventually, the expansion of Europe also turned south. This time the colonizing powers resided in temperate Europe; and they attempted to impose their own landscape ideal on the northern Mediterranean either outright through colonial institutions or covertly through the academic-sanctioned norms of forestry. The Mediterranean found itself in the backwash of Europe's second great age of discovery and the impulses that sent its imperium sprawling across the Earth's continents.

Perhaps the most interesting study is France's *grand traverse* from central Europe to central Africa. Expanding southward, France acquired Mediterranean lands within its national estate (through the one serious breach in the northern fringe of mountains). Its attempt to impose a normative landscape cultivated in the Paris basin when extended into Provence and Languedoc, not least because of endemic burning. Then France acquired Corsica in 1769, which became the scene of a ceaseless fire insurgency. Then Algeria, which became one long firefight. Then Morocco, another Mediterranean landscape, and a fire protectorate. And finally the Sahel and the equatorial tropics, subject to wet and dry seasons and hence to a predisposition to burn as robust as that of the Mediterranean. The colonial campaigns to eliminate fire that followed proved not only hopeless but damaging in their own right. The one great innovation that emerged was the stimulus Greater France gave to the first systematic attempt to tabulate fire throughout the Earth, Georges Kuhnholtz-Lordat's *Le Terre Incendiée* (1938) (Pyne 1997).

It matters that much of the supervision of this ordeal fell to foresters. They had become, by self-proclamation as much as any bona fide reason, the self-designated oracles and engineers of free-burning fire, which they hated and distrusted, seeing in fire a vital means by which farmers converted forest to field and pastoralists replaced

woods with forage. In both France and Germany forestry became an organ of the state, and as the state extended its reach to overseas colonies, foresters often became proconsuls of the environment. Some lands they seized and isolated as gazetted forests; others they sought to strip of burning, and hence to render them "modern" (they declared the explicit divide between a "rational" landscape and one based on inherited superstition was fire). Most especially they railed against transhumance, with its tendency to burn out long corridors across the landscape. They denounced rural burning, even the *petit feu* that had long characterized Mediterranean France. They demonized the goat (Grotenfelt 1899; Pyne 1997).

When Britain acquired Mediterranean colonies, as waystations to India (through the Suez Canal), it proceeded along similar lines. The islands became miniatures of Mediterranean fire history. As with the French colonies, British Cyprus soon sparked a ceaseless insurgency of folk burning in which every act taken to suppress fire only provoked an equal reaction to reinstate it. The land was intrinsically fire-prone; and so long as it was populated with a people who needed fire to make those scenes habitable for farming and especially grazing, it would burn, no matter how many firefighters foresters committed to the attack and how often foresters might condemn the burning as converting isles into cinders (Thirgood 1987).

But more powerful than direct rule was the indirect influence of modernity, particularly liberalism in both its political and economic avatars. Greece achieved independence from the Ottoman Empire, and then became subject to a renewal of ideas from the major European powers. Italy achieved union. Spain gradually sloughed off the most moribund of its monarchical state, and commenced *desamortización*, the Iberian cognate to Britain's enclosure movement, a shock treatment for the traditional subsistence landscapes, forcing them into a market economy. Apart from elitist theories and the fulcrum of commerce, there was forestry.

Even where foresters were not the direct hand of an imperial power, they were self-styled agents of modernity, engineers of wooded lands, and they came to advise the more progressive states about reorganizing their environment. They made the silva not merely one of three landscape modes but demanded that it be dominant. Where agronomists had once considered the silva as an appendage to farming, foresters now established the tree as the measure of environmental health and resurveyed the panorama of agriculture through the conceptual theodolites of silviculture. They saw the Mediterranean's fires, like its malarial swamps, as both a cause and a symptom of its immense malaise.

This frontier was first fought in Mediterranean France, particularly in Provence, where abundant shepherds littered the landscape with fire and the mistral could occasionally whip those benign flames into catastrophe. By the 1880s industrialization was already underway: steam was replacing muscle, commercial woods were competing with pasture, and foresters were actively squelching open fire on the land. France was the earliest and foremost of the Mediterranean forestry powers since it alone had a contiguity of land and institutions with the core of temperate Europe.



In 1885 Major Frederic Bailey led a cadre of forestry cadets from their classrooms at Nancy to the French showcase for fire control, the forest at Esterel. "Until we came to the Maures and Esterel, we had no idea that forest fires were such a

serious question in any part of France, or that such complete arrangements existed for their suppression." But a bout of drought, high winds, traditional burning, and a fast-changing countryside had sparked major outbreaks in 1870 and 1877, and the response was to enact legislation in 1870 (amended in 1883) that created a model for fire's control and hence for forestry's desired dominance over the countryside (Bailey 1887).

Fire protection resembled a gendarme, or an army of occupation, that sought to prevent bad behavior and enforce good. The new fire codes prohibited burning with 183 m of a forest boundary or outside the designated season, and then only with permits, with severe penalties for violations. To prevent accidental fires (or arson) foresters laid out a network of roads, trails, and 15–40 m wide firebreaks; and privately owned lands adjacent had to install similar measures. To detect fires foresters maintained a system of hilltop lookouts and ceaseless patrols during fire season. If a forest guard spotted a fire, he attacked it, and if unable to exert control, would sound an alarm for others, and then for neighboring villagers, and finally the army. If direct attack failed, then defenders resorted to counterfires, typically from roads or firebreaks.

There was one notable adaptation of traditional practice, "believed to be peculiar to the Maures and the Esterel," that involved *petits feux*, or small fires. Foresters divided areas into vertical strips, and then burned a strip from the top down, beginning with those adjacent to the cleared firebreaks. Each year, in December, January, or February, a new strip was burned (the whole cycle requiring six or seven years), and sometimes more frequently "to prevent the undergrowth of shrubs from becoming so dense and tall, that the entry of an accidental fire would be attended with disastrous consequences." Typical patches were one or two acres in size. The arrangement made the task of attacking potential conflagrations an "easy matter." Still, forestry dogmatism condemned the practice as "detestable from all points of view," and so it was taught in the lecture halls of Nancy (Bailey 1887).

Despite its Cartesian logic, the system was rarely enacted outside special sites (the Esterel forest comprised 6,744 ha). Traditional fire practices coexisted uneasily with modern variants, and both survived because the general countryside was still sufficiently cultivated that opportunities for escapes and infernos were rare. Still, change was underway, and when the population could no longer contain the mixed Mediterranean biota, both the indigenous and the exotic plantations, fires could break free. They did so, spectacularly example, in 1918 and 1919 after war privations and a lessened on-site population allowed the maquis to run riot and the mistral blew *petit feu* into conflagrations (Pyne 1997).

Wild fires were thus an expression of social order – or, as critics saw it, of disorder. It was a perception that the unending recourse to incendiary warfare in the Mediterranean helped confirm. The felling and burning of Mediterranean woodlands, in particular, seemingly echoed the sacking and burning of its civilized citadels. Even Homer had likened an enraged Achilles to a conflagration. In a landscape of anthropogenic fire, the hand that holds the torch controls the shape of the countryside much as the chisel in the hand of a sculptor turns marble into statue.

## 2.8 Industrialization and the Great Delamination

In the 19th century the Mediterranean's characteristic disturbance regime commenced a slow but radical transformation. Industrialization and the controlled combustion of fossil fuels began deranging what millennia of Mediterranean agriculture had for so long and so meticulously ordered (Pyne 1997; Pereira et al. 2006).

The weapons of conquest were chemical fertilizers, electricity, the internal combustion engine, and mass commerce overseas, not for spice, bullion, and slaves, but for cotton, steel, oil, machinery, and televisions. Under such blows village life cracked; the countryside began to empty as urbanization replaced war, disease, and emigration as a demographic forcer; intensively managed garden plots became surplus and increasingly superfluous. Railroads replaced the hoof-worn routes of transhumance. Tourists substituted for agricultural laborers and shepherds moving with the seasons, while bird watchers and skiers supplanted the resin-tappers and charcoalers of the past. Forests rose, both deliberately and haphazardly, on abandoned vineyards and pastures.

At different places, at different rates, the old order began to crumble, dissolving like a fresco exposed to corrosive steam. The tiles of the old mosaic fell out. Many long-tended landscapes were left to the very old, the very young, the exurban, and the sightseer. If not truly empty, they were emptied of the fidgeting hands and busy hoofs that had so long shaped them. A resurgent biota fluffed landscape after landscape with combustibles. In this evolving scene the fuels were robust, the fires constant, and the ability to combat them insufficient. The old rural order of fire control by close cropping, browsing, and *petit feu* unraveled; a new one, based on air tankers and firetrucks (internal combustion engines all), foresters, and prescribed burning had not created a working surrogate. Feral fire replaced domesticated fire, blotching the littoral like a biotic rash. The greater the disintegration of rural landscapes, the more rabid the fires. The worst outbreaks have exhibited the environmental equivalent of a civil war.

The unraveling of Iberia has been especially notable. The collapse of the Salazar and Franco dictatorships, and the subsequent accession into the European Union, have unleashed economic forces that elsewhere came more incrementally. The traditional countryside found itself suddenly removed from an oppressive (or at least obsessive) order of regulation: the political liberation of society expressed itself environmentally as the countryside depopulated, workers poured into metropolitan centers, and the central state devolved power to the provinces. Equally, old emblems of forced change from the *ancien regime*, such as the attempt to replace communal lands with plantations of eucalypts, became sites of protest, and of political arson.

Untended, the countryside has overgrown with woody weeds, and where the climate supports lush growth, the outcome was a veritable riot of revanchist flora, followed by a plague of escalating burning that firefighting forces could neither prevent nor suppress. Regional terrorism pales in comparison to the damages. Portugal's Tras o Montes and Spain's Galicia have suffered particularly; probably no countries have endured catastrophic fires on a comparable scale. The old order was

unacceptable. A new one has not yet arisen to replace it. Simply investing more in fire suppression cannot hold the flames.

The observation of Theophrastus that fire would seek out the voids – the destitute sites, the emptied landscapes – has proved once again prophetic. Probably not since the plague of Justinian had the landscape known such a sudden vacuum. But this time the new landscape would not be built out of the materials of the old, as the stones of pagan temples had gone into erecting Christian cathedrals. Some new technologies would substitute. What stalled a complete disintegration, for example, was the European Union's general agricultural policy.

What endured was the requirement that the ecological order would be inextricably intertwined with the social order, that fire's regimes would reflect humanity's. Fire's ecology and fire management's precepts, both would derive from an underlying social substrate. That had been Europe's logic from ancient times; the Mediterranean, with its fire-enhancing climate and biota, displayed that understanding with rising flames.

## 2.9 *Vulcan et Vesta*: Mediterranean Europe, Fire, and Earth

What is fire to the Mediterranean, and the Mediterranean to fire?

It is a major biota, one extraordinarily rich in species, and one inextricably intertwined with fire dynamics. No explanation for the Earth's Mediterranean biomes can succeed without incorporating fire; and no theory of fire ecology can thrive without explaining those landscapes. The ancient observation of Theophrastus remains true: "(Only) fire is naturally able to generate itself and to destroy itself: the smaller fire generates the larger, and the larger destroys the smaller."

It is no less a place of exceptional human history. The Mediterranean was a hearth both for agriculture and for European civilization; and the world's five Mediterranean regions have been prime sites for extra-European colonization. They all feature important fire institutions. They remain today exemplary arenas for fire management within the continents of which they are a part. The Cape of Good Hope has made South Africa the premier focus for fire ecology and management in Subsahara Africa; California has exerted a similar role for the United States; Chile, for South America; its southwestern and southeastern sectors, for Australia; and of course the Mediterranean *sensu strictu,* for Europe. The modern cycle of international fire symposia began with a 1977 conference on fire in Mediterranean-climate lands, succeeded by another in 1983, and others since. Perhaps only the vastly more expansive boreal has attracted more fire conferences.

But the Mediterranean's greatest contribution may lie within the realm of ideas; ideas of how fire functions in nature and how it works in society. In this regard the Mediterranean experience has served as both paradigm and paragon. The landscape history of the Mediterranean has long furnished the prevailing notions of Garden and Desert, of a natural Eden and a Fall into anthropogenic ruin, that have underwritten almost all narratives of Western environmentalism. This declensionist model has

also informed academic understanding of how fire affects the Mediterranean biota: the ideal, “natural” order is one of thick woods which, under the blows of axe, hoof, and torch, degrade into more diminutive shrubs and finally into patchy scrub, prickly phrygana, and inedible weeds. Instead of a malleable landscape capable of assuming many forms, but one so long used and fatigued that it has lost much of its elasticity, the prevailing model promotes a notion of singular directionality. It insists that the biota must move up or down when it might rather be seen as shifting horizontally. In this phrasing fire’s presence drives the system down, while its suppression allows it to rise; there is no sense that it is a catalyst that, like iron in a forge, helps its human artificers fashion it into different forms. This declensionist conception, as paradigmatic as a Latin noun, has been one of the Mediterranean’s dominant fire exports.

More usefully, the Mediterranean can profoundly challenge prevailing assumptions, embedded deeply in the genetic fiber of the industrial firepowers, that the core landscapes of analysis must stem from wilderness, that removing the human presence is the surest corrective to pyric imbalances, and that fire must, in its essence, be natural in order to serve ecological goals. The Mediterranean suggests otherwise. It says that the core landscape of any meaning is cultural and that the defining fires are anthropogenic. Such conceptions are foreign to North American and Australian fire philosophies, but they are not alien to northern Europe, and they merge seamlessly into the fire histories of South America, Africa, and Asia. More than anywhere else in Europe the Mediterranean illustrates the ancient European understanding of fire as primarily a cultural construction.

Vulcan and Vesta – the Roman god of the forge and the goddess of the hearth, fire as a tool and fire as a symbol, with both in the service of society; this is the European legacy for understanding fire. The hearth, the furnace, or their domesticated landscape analogue, the cultured field, is where fire should reside, not free-burning over untrammeled realms of geography. It is a vision of fire as instrumental and as a power that must be disciplined by social prescriptions. If fire could be replaced by better tools, it should be. A corollary is that fire thus becomes, as European thinkers have always insisted, an index of social order (Goudsbloom 1992).

It is not hard to see such notions at work today. The feral fires of recent decades in the Mediterranean are, in fact, a measure of social unrest; they are as fully an outcome of the global economy as of the global climate. They will be contained not by force of fire-suppression arms, except fleetingly, but by reconstituting a matrix of patchy land use. Like petrified wood in which silica replaces lignin molecule by molecule while preserving the gross structure, the emerging European landscape may find industrial surrogates. It may be, too, that controlled burning vanishes, or more properly gets sublimated into machines as part of a general reversion from a fossil-fuel economy. Even our globally-warmed climate, after all, now falls under the purview of humanity’s combustion habits, such that there are plenty of European intellectuals who would be pleased to see a final abandonment of open burning in the drive for a carbon-neutral world.

Whether or not such views prevail, they are strongly valenced to the European Mediterranean. Whatever fire scene eventually evolves in the region, it is likely to

emphasize that control resides in the social creation of the landscape and that fire – anthropogenic fire – is something that expresses the character of its sustaining society. Fire, after all, is only what its context makes it. And as Theophrastus reminds us, it thrives most boldly in the empty places society leaves.

**Acknowledgements** This essay builds from my summary of Mediterranean fire history published in *Vestal Fire. An Environmental History, Told Through Fire, of Europe and Europe's Encounter with the World* (Seattle: University of Washington Press 1997): 81–146. Readers interested in background sources should consult the notes and bibliography that accompany that study.

# Chapter 2

| Q. No. | Query |
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| AQ1 | "Frazer, 1995" is not listed in the reference list. Please provide. |
| AQ2 | Please specify whether “Trabaud, 1987” is “1987a” or “1987b”. |
| AQ3 | "Bailey 1885" is not listed in the reference list. Please provide. |

# Chapter 3
# Fires and Landscape Conservation in Mediterranean Ecosystems

**Jan W. van Wagtendonk**

**Abstract** Protected areas are some of the last remaining areas on Earth where fire can play its natural role at a landscape-scale. International Union for Conservation of Nature (IUCN) has developed a system for categorizing protected areas. The role fire can play in the various categories depends on the management objectives of the category, the size of the individual units, and the laws and policies of the country in which the unit is located. An analysis of all the IUCN protected areas showed that 505 areas had the potential for conserving landscape fire. Areas in Europe, Africa, South America, Australia, and North America show promise for being able to include fire in the conservation of landscapes. Examples from South Africa, Australia, and the United States show how fire can be incorporated at the landscape scale. Future challenges include increasing urban encroachment, climate change, and air pollution. Society will have to deal with these challenges if fire is to continue its essential ecological role in Mediterranean ecosystems.

## 3.1 Introduction

Protected areas are some of the last remaining areas on Earth where fire can play its natural role at a landscape-scale. The encroachment of human development, including conversion of wildland to agriculture, urbanization, and pollution, are combining with global climate change to make landscape conservation a critically important endeavour. In the Mediterranean regions, encroachment into natural areas is particularly acute.

Landscapes and the ecological processes that perpetuate them need to be protected or they will be lost. Landscape conservation depends on the presence of all of the ecological processes, for without any one of them a different landscape

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would be formed. This is especially true for fire, a process that has been treated with ambivalence throughout human history. Excluding fire from a fire-prone landscape is akin to removing precipitation or sunlight – a completely different landscape would evolve. Without adequate precipitation, forests would become deserts and, without sunlight, plants and animals would cease to exist. Similarly, without fire many forests would become thickets of shade tolerant trees, and large accumulations of fuel would predispose the forest to catastrophic fire. Large homogeneous stands of shrubs from which fire has been excluded would become highly flammable as the proportion of dead material increases with age. Coupled with extreme weather and ignitions by humans, these shrublands often burn with intensities not seen in the natural world. Landscapes such as these cannot be protected in perpetuity without all of their component parts and processes, especially fire.

In this chapter, we will explore the role protected areas in regions with a Mediterranean climate have in conserving landscapes with particular emphasis on the perpetuation of natural fire regimes. We will begin by describing the different types of protected areas and how well those areas are represented in the various countries in the Mediterranean climate region (Fig. 3.1). That will be followed by examples of fire programs in protected areas that encompass fire in their management strategies. Finally, we will discuss the future of fire in protected areas for landscape conservation.

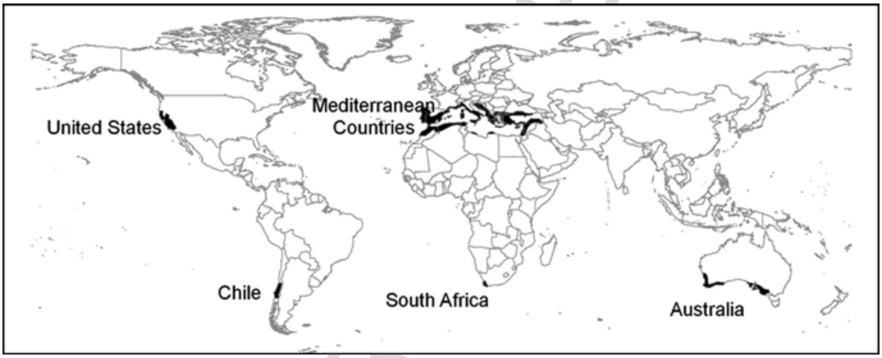


**Fig. 3.1** World map showing Mediterranean climate regions

## 3.2 The Role of Protected Areas in Landscape Conservation

The International Union for Conservation of Nature (IUCN), an organization devoted to finding practical solutions to environmental problems, is concerned with the protection of all types of animal and plant species on the planet and all types of ecosystems that exist on Earth. In conjunction with the World Commission on Protected Areas (WCPA), the IUCN has developed a system for categorizing protected areas. These categories range from strict nature reserves to managed resource protected areas. The role fire can play in the various categories depends on the man-

agement objectives of the category, the size of the individual units, and the laws and policies of the country in which the unit is located.

The six categories range from strict nature reserves where human use and visitation are restricted and controlled to managed resource areas where sustainable use and exploitation are the objectives. Each category has distinguishing objectives, features, and role in the landscape. The categories are unique and have specific issues for consideration. Landscape fire might or might not be appropriate in any particular category or in any particular country.

### 3.2.1 Category Ia: Strict Nature Reserve/Wilderness Areas

Strict nature reserves are areas that are set aside to protect biodiversity or geological and geomorphological features whose persistence is incompatible with very little human use (IUCN 1994). These areas serve as reference areas for scientific research and monitoring. The primary objective of Category Ia areas is to conserve regionally, nationally, or globally outstanding ecosystems. These areas are distinguished by having a largely complete set of native species and intact ecological processes. Presumably, naturally occurring fire should be included as an ecological process. On the other hand, human-induced change as a result of fire exclusion could compromise the objective of the area. In reality, Category Ia areas are often too small to allow for the natural role of fire, or fire might conflict with a specific scientific objective of an area.

### 3.2.2 Category Ib: Wilderness Area

Wilderness areas are usually larger than strict protected areas and some recreational use is permitted. The primary object for Category Ib areas is to protect the long-term ecological integrity of large, mainly undisturbed ecosystems (IUCN 1994). Additionally, wilderness areas should be largely undisturbed by human activity and be predominantly influenced by natural forces and processes. Again, although not specifically mentioned in the IUCN (1994) guidelines, fire must be considered one of those ecological processes. The size and management objectives for wilderness areas make these areas particularly suited for landscape conservation that includes fire.

### 3.2.3 Category II: National Park

National parks are usually large natural or near natural areas set aside to protect large-scale ecological processes along with the complement of species and ecosystems characteristic of the area (IUCN 1994). They also provide spiritual, scientific, educational, and recreational opportunities. Their primary objective is to protect native biodiversity and ecological processes. Compatible human use that

does not impair the diversity or processes is permitted. National parks are usually large enough to conserve a functioning ecosystem, allowing native species and communities to persist for the long-term with minimal management intervention. Implicit in the definition of a national park is the role they play in large-scale conservation opportunities where natural processes such as fire can persist in perpetuity.

### 3.2.4 Category III: Natural Monument

Category III protected areas are set aside to protect a specific natural feature such as a geological formation, cave, landform, or grove of trees (IUCN 1994). They usually are small and have high public value. The primary objective for natural monuments is the protection of the feature for which it was established. Secondary objectives include providing for biodiversity, protecting natural sites that have cultural values, and facilitating spiritual and cultural activities. As such, the opportunities for landscape-scale fire are usually not available. However, in large monuments where objectives would permit the use of fire, fire could be allowed to play a more natural role.

### 3.2.5 Category IV: Habitat/Species Management Area

Category IV areas have the specific objective of protecting particular species or habitats (IUCN 1994). These areas are usually fragments or incomplete ecosystems. Human intervention is often necessary to maintain the habitat requirements of the particular protected species. If the area is large enough, fire can be used as a management tool, but rarely is landscape-scale fire allowed to play its role.

### 3.2.6 Category V: Protected Landscape/Seascape

Protected landscapes include areas where the interaction of people and nature over time has produced a unique landscape where protecting that interaction is vital to sustaining the area (IUCN 1994). The primary objective of these areas is to protect and sustain the landscapes and the interactions that created them. Although these areas would be appropriate for use of fire as a cultural practice, landscape-scale fire would probably not be applied.

### 3.2.7 Category VI: Managed Resource Protected Area

Managed resource protection areas are generally large with a combination of natural area protection and sustainable resource management (IUCN 1994). Exploitation of resources is one of the main purposes of these areas where it is compatible

with nature conservation. In most cases, landscape-level fire would conflict with the objectives of Category VI areas.

## 3.3 Protected Areas in Mediterranean Ecosystems

Mediterranean ecosystems are well represented by protected areas. These areas present the opportunity to include fire in landscape conservation efforts. Digital maps of protected areas were obtained from the World Database on Protected Areas maintained by IUCN World Commission on Protected Areas and the United Nations Environment Programme World Conservation Monitoring Centre (WDPA 2008). Although all categories of protected areas were represented in the database, the category for some areas was unknown.

In order to determine which protected areas were in regions with a Mediterranean climate, the protected area map was intersected with the Koppen-Geiger climate classification map obtained from Harvard University Center for International Development (CID 2008). Two climate zones were selected to represent the Mediterranean areas. Zones CSa and Csb occur around the Mediterranean Sea in Europe and Asia and between the latitudes of 30° and 45°.along the western coasts of Africa, Australia, South America, and North America. Summers are hot and dry except along the coasts, where summers are milder due to the proximity to cold ocean currents. For North America, the two climate zones were reduced by eliminating the area covered by Trewartha's (1981) temperate oceanic climate zone..This removed the area north of the border between California and Oregon where there is a significant change in vegetation..

These maps were then intersected with a map of the countries of the world obtained from Environmental Systems Research Institute (ESRI 2008). The three maps were reprojected to the WGS 19884 PDC Mercator projection before being combined. The combined layers were then used to determine the number and extent of all protected areas in each country that were within the Csa and Csb zones (Table 3.1). While it is recognized that there are errors in each of the maps, the errors were applied consistently across all countries.

Based on the primary objectives and distinguishing features, protected areas in Categories IV, V, and VI were not considered appropriate for the application of landscape-level fire. In addition, areas that were less than 10 $km^2$ in size would be too small to allow natural fires to run their course. This size is based on experience in Yosemite National Park in California, USA, where no lightning fires that have been allowed to burn largely unimpeded for over 30 year have exceeded 0.5 $km^2$ (van Wagtendonk and Lutz 2007). By the time fires reach that size, they run into a previous fire and either burn out or are greatly reduced in intensity, Collins et al. 2008). After eliminating the categories in which landscape fires would be inappropriate and those too small to sustain those fires, only 505 protected areas covering nearly 90,000 $km^2$ remain world wide that have the potential for conserving landscape fire.

**Table 3.1** Protected areas in Mediterranean climate regions

| | IUCN Category | | | | | | | | Total | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Category Ia | | Category Ib | | Category II | | Category III | | | |
| Country | no. | km$^2$ | no. | km$^2$ | no. | km$^2$ | no. | km$^2$ | no. | km$^2$ |
| Albania | 3 | 344 | – | – | 11 | 1,763 | 2 | 93 | 16 | 2,200 |
| Algeria | – | – | – | – | 1 | 253 | – | – | 1 | 253 |
| Australia | 170 | 19,172 | 9 | 5,696 | 23 | 2,696 | 134 | 2,982 | 336 | 30,546 |
| Bosnia | – | – | – | – | 1 | 134 | – | – | 1 | 134 |
| Bulgaria | 1 | 28 | 3 | 74 | 1 | 114 | 3 | 81 | 8 | 297 |
| Chile | – | – | – | – | 5 | 435 | – | – | 5 | 435 |
| Croatia | – | – | – | – | 1 | 322 | – | – | 1 | 322 |
| Cyprus | 1 | 50 | – | – | 3 | 218 | – | – | 4 | 267 |
| France | – | – | – | – | 2 | 1,337 | – | – | 2 | 1,337 |
| Greece | – | – | – | – | 11 | 1,578 | 1 | 114 | 12 | 1,692 |
| Israel | – | – | – | – | 1 | 45 | – | – | 1 | 45 |
| Italy | – | – | 1 | 271 | 4 | 2,494 | 1 | 41 | 6 | 2,807 |
| Macedonia | – | – | – | – | 3 | 1,127 | – | – | 3 | 1,127 |
| Montenegro | – | – | – | – | 1 | 2,304 | – | – | 1 | 2,304 |
| Morocco | – | – | 1 | 39 | – | – | – | – | 1 | 39 |
| Portugal | 1 | 131 | – | – | 2 | 1,267 | 2 | 27 | 5 | 1,424 |
| S. Africa | – | – | 2 | 642 | 6 | 854 | – | – | 8 | 1,496 |
| Span | – | – | – | – | 3 | 1,098 | – | – | 3 | 1,098 |
| Tunisia | – | – | – | – | 1 | 17 | – | – | 1 | 17 |
| USA | 31 | 616 | 61 | 37,549 | 7 | 2,648 | – | | 99 | 40,813 |
| Total | 207 | 20,341 | 77 | 44,271 | 87 | 20,702 | 143 | 3,338 | 514 | 88,652 |

### *3.3.1 Europe*

Europe has many protected areas that are large enough to have landscape-scale fire programs. Although these areas are designated to preserve the biological diversity in the ecosystems and the natural processes occurring in them, natural fire is currently not a management option. However, because these areas are important tourist attractions and contain many cultural features, suppression is the only fire management practice.

It is evident from the vegetation, that fire has played a role in the evolution of many of the species that occur in these areas. Black pine (*Pinus nigra*) is present in many of the protected areas and has been shown to experience periodic light surface fires in Spain (Fulé et al. 2008). Remnant stands of Scots pine (*Pinus sylvestris.*) indicate the former presence of stand replacing fires. Although these fires would be difficult to reintroduce, fire would be necessary in the long run to maintain the biodiversity of this forest. Stands of black pine and Brutian pine (*Pinus brutia)* in Cyprus also indicate some adaptation to fire (Fulé et al. 2008, Spanos et al. 2001). Aleppo pine (*Pinus halepensis*) occurs in Greece and is a fire prone species that regenerates well after fire (Daskalakou and Thanos 2004). In Portugal, stone pines (*Pinus pinea*) have serotinous cones. However, care must be taken when applying

landscape fire because extensive fires can reduce the regeneration of this species (Rodrigo et al. 2007).

### 3.3.2 Asia

The only protected area in Asia of the correct size and category is the Har Hakarmel Nature Reserve in Israel. However, it is a wetland and an inter-tidal reserve. Therefore, it would not burn.

### 3.3.3 Africa

In northern Africa, Algeria, Morocco, and Tunisia each have one protected area in the Mediterranean climate zone. These areas contain varying amounts of remnant stands of Atlas cedar (*Cedrus atlantica*), black pine, maritime pine (*Pinus pinuster*), and Spanish fir (*Abies pinsapo*). Although it is not known what role fire played in these stands, fire has caused a loss of biodiversity of similar northern Moroccan forests (Ajbilou et al. 2006).

Two national parks and 15 nature reserves with Mediterranean climates in South Africa are large enough for landscape level fire. Agulhas National Park and Table Mountain National Park both have active programs that manage fire in the fynbos, a fire adapted shrubland type (Forsyth and van Wilgen 2008). Vegetation in the nature reserves consists of fynbos, succulents, dwarf trees, and shrubs (Fig. 3.2).

**Fig. 3.2** Mountain fynbos in the Jonkershoek Valley, Stellenbosch, South Africa. Darker shrubs are *Protea neriifolia* and *Protea repens* (both obligate re-seeding plants). Lighter coloured shrubs are *Protea nitida* (a resprouter after fire). Photo by B.W. van Wilgen

### *3.3.4 Australia*

Australia has 207 protected areas in Category Ia, 11 in Category Ib, 50 in Category II, and 1,339 in Category III. Most of these areas are located in Western Australia and South Australia, with some occurring in Victoria. Nature reserves (Ia) and heritage agreements (III) make up the majority of the protected areas. Most of the natural vegetation in these areas is classified as either eucalypt forests or mallee woodlands and shrublands. Many opportunities are available for landscape level fire.

### *3.3.5 South America*

Five national parks in Chile are large enough to accommodate landscape level fire. Mixed forests of monkey-puzzle (*Araucaria araucaria*) and Antarctic beech (*Nothophagus antartica*) and Campos grasslands are present in each of the national parks. Studies have shown that fires have occurred in the mixed forests periodically (Gonzáles and Veblen 2006) and that the forests expand into the grasslands when the fire return interval is reduced (Behling et al. 2003).

### *3.3.6 North America*

The Mediterranean climate zone in the United States includes 63 wilderness areas (Ib), four national parks (II), and one national seashore (II) large enough to sustain landscape level fire. Four wilderness areas are located in national parks, 44 occur in 16 national forests, and 15 occur in Bureau of Land Management districts. Vegetation ranges from coastal forests to foothill chaparral and montane forests. Fire regimes vary between each of these vegetation types (Sugihara et al. 2006).

## 3.4 Examples of Fire Programs in Protected Areas from Around the World

No countries in Europe, Asia, or South America have landscape level fire programs. However, prescribed burning is used extensively in South Africa, Australia, and the United States. In addition, there are active programs to allow naturally-ignited fires to run their course under prescribed conditions in the United States.

### *3.4.1 South Africa*

Table Mountain National Park is located on the western cape of South Africa. The predominant vegetation is fynbos. Forsyth and van Wilgen (2008) analyzed 373 fires

>1 ha that occurred in the park between 1970 and 2000. They found that the mean fire rotation was 22 year, and that these fires burned primarily in the summer or autumn. Sixty one prescribed fires (both controlled and escaped) accounted for 21% of the area burned, while four fires caused by lightning and one by a falling rock contributed another 1%. Fires from unknown causes burned the remainder (Forsyth and van Wilgen 2008). Most of the fires were small and burned relatively little area, while a few large fires burned the majority of the area.

The park has had a fire management program that emphasized prescribed burning since the 1970s.to rejuvenate the fynbos, to reduce fire hazard, and to control invasive alien plants (Richardson et al. 1994). The program emphasized burning catchments at regular intervals. Over the years of their study, Forsyth and van Wilgen (2008) found that although the use of prescribed fire had decreased, the intervals between fires in the fynbos decreased from 31.6 to 13.5 year as a result of unplanned wildfires. The shorter return intervals were of concern, because they can eliminate some native obligate seeders that are dependent on the natural return interval and because short intervals can increase the presence of non-native invasive plants.

One of the biggest issues facing land managers wanting to reintroduce fire in South Africa is the invasion of fynbos by large, fire-adapted trees. There are only a few areas of fynbos where invasion levels are low enough to support landscape-level fire regimes that will not be complicated by invasions (B. W. van Wilgen; Council for Scientific and Industrial Research in South Africa, Natural Resources and Environment; personal communication).

Forsyth and van Wilgen (2008) recommend increased use of prescribed fires during the summer and autumn at intervals consistent with the natural fire regime. They further recommend that areas where the fire interval has become longer than 35 year be identified and monitored to ensure that their ecological integrity is maintained. Finally, they recommend natural ignitions be allowed to burn under prescribed conditions and that human-caused fires be suppressed where appropriate. Similar recommendations have been proposed by Brown et al. (1991) for the Cederberg Provincial Natural Area. If these recommendations are followed, landscape level fire will be able to maintain natural fire regimes in the South African Mediterranean protected areas.

### *3.4.2 Australia*

Prescribed fires have been used in Australia since the early 1930s to reduce fuel accumulations in an effort to mitigate the effects of wildland fires (Hodgson 1967). In Western Australia, active fire management programs exist in several nature reserves and national parks. There is concern, however, that prescribed burning at too short an interval could be deleterious to native plant and animal species (Burrows et al. 2008, Christensen and Maisey 1987). Burrows et al. suggest that the minimum

**Fig. 3.3** Experimental fire in Jarrah forest of Western Australia, Project Vesta, 1999. Photo courtesy of Australian National University, Research School of Physical Sciences and Engineering

interval between fires should be greater than the time to first flowering in order to conserve plant diversity. The Perup Nature Reserve was burned frequently from the late 1930s to the mid 1960s (Shepherd et al. 1997). Cyclic spring burning to reduce fuels was initiated in the 1960s, but it has since been recognized that a combination of intense autumn fires and milder spring burns was necessary to maintain thickets and stimulate legumes required by herbivorous marsupials (Christensen and Maisey 1987) (Fig. 3.3).

Fire management plans now provide for fire regimes that include a diversity of frequency, season, and intensity (Burrows et al. 2008). Such regimes provide for a mosaic of vegetation and habitats while at the same time managing fuel accumulations. The application of similar management programs to other protected areas in Australia will accomplish the goal of maintaining fire at a landscape scale. Future plans should include the incorporation of lightning fires in addition to prescribed fires.

### 3.4.3 United States

Although prescribed fire had been in use in the United States since the 1930s, landscape level fire programs did not come into existence until the late 1960s. Three national parks within the Mediterranean climate zone in the Sierra Nevada of California led this effort. Prescribed burning began in Sequoia and Kings Canyon National Parks in 1964 and in Yosemite National Park in 1970. Programs to allow lightning caused fires to run their course under prescribed conditions began in 1968 and 1972 in the respective parks (van Wagtendonk 2007). From the onset, these programs had as its objective the unimpeded interaction of native ecosystem processes and structural elements (Parsons et al. 1986).

Interruption of the natural fire regime, reflected in departures from normal fire return intervals, is a major challenge for park fire managers. Areas that have missed multiple fire return intervals are more susceptible to stand-replacing wildland fires, which are uncommon in natural surface-burning fire regimes. Prescribed fire treatments are focused on those areas with the greatest fire return interval departures, while areas that are within two fire return interval departures are usually placed within fire use zones (van Wagtendonk et al. 2002).

To analyze fire return interval departures in the Sierra Nevada parks, fire managers have used a geographic information system (GIS) model based on a method originally developed in Sequoia and Kings Canyon national parks (Caprio et al. 1997). This model combines information on fire history and fire ecology to assess the ecological condition of all vegetation communities, using departures from the natural fire return intervals as an indicator of change. The analysis consists of four steps: (1) vegetation types are defined on the basis of similar fuels and fire behavior; (2) fire return intervals based on fire scar studies are assigned to each type of vegetation; (3) the number of years since an area last burned is determined from fire history maps dating back to 1930; and (4) departures from the natural fire interval are calculated using the return interval. Landscape-scale changes in the fire regime are characterized by an analysis of departures from the fire return interval had fires been allowed to burn naturally. In general, the further vegetation communities depart from their natural fire regimes, the more unnatural conditions prevail and the higher the risk of the occurrence of a stand replacement wildland fire which is not natural to surface burning fire regimes.

Since the inception of the fire management programs over 30 years ago, fire has been restored to 34,470 ha in Yosemite and 52,291 ha in Sequoia and Kings Canyon. As the programs have evolved, certain patterns are beginning to develop. For example, Collins et al. (2007) found that spatial patterns of severity of landscape level fires in Yosemite and Kings Canyon were affected by relative humidity and vegetation type. Equally interesting was the interaction of fires where they encountered previously burned areas in Yosemite (Collins et al. 2008). When the amount of time between successive adjacent fires was under 9 years, and when fire weather was not extreme, the probability of the latter fire burning into the previous fire area was extremely low (Fig. 3.4).

Prescribed fires and suppressed wildfires do not necessarily mimic the fire regime of natural landscape fires (van Wagtendonk and Lutz 2007). In Yosemite, prescribed fires started both earlier and later than natural fires, had shorter return intervals, and resulted in lower severity. Wildfires were larger than natural fires and had the largest percent area burned at moderate and high severity. Wildfires also had larger and more uniform moderate and high severity patches.

These programs have shown that fire can be restored at the landscape-scale. Critical to their success has been the large size of the protected areas, the absence of intermixed human development, and fuel levels that are within their natural range of variation.

**Fig. 3.4** The 2,927 ha Hoover Fire burning under prescribed conditions in Yosemite National Park in 2001. The area in the center with the large smoke column had not been burned for 13 years, while the area to the right had been burned in the past 7 years

## 3.5 The Future of Fire in Protected Areas for Landscape Conservation

Many factors will make it increasingly difficult to conserve fire and landscapes in the future. The encroachment of human development into wildlands is one of the most daunting challenges. When people build near natural areas, they bring with them the expectation that their homes will be protected from fire. This often precludes the land manager from applying landscape level fire for fear that the fire might escape and destroy life and property. Each new catastrophic fire increases the clamor to do something about fuels. The most immediate problem exists around developments and areas of high societal values, such as cultural sites and endangered species habitats. Mechanical removal of understory trees followed by prescribed burning is the most likely method to succeed in these areas. Less compelling are treatments in remote areas where there is less development and access is difficult. Prescribed burning and the use of naturally occurring fires are more appropriate in areas beyond the urban-wildland interface

Many at-risk species occur in Mediterranean ecosystems, and some of these are dependent on fire-maintained habitats. Concurrent changes in fire regimes and vegetation have resulted in region wide changes in wildlife habitat. The question becomes how to restore landscape level fire without adversely affecting at-risk species and their habitats. To do nothing only makes the situation worse, predisposing the species and habitats to destruction by catastrophic fire. These species

evolved with fire, and the answer must include fire. Care must be taken, however, to ensure that fragmented populations are not adversely affected by fire treatment activities.

One of the biggest impediments to allowing wildland fires to burn under prescribed conditions is the restriction on air quality. Smoke is a by-product of burning, whether it comes from a prescribed fire, a wildland fire burning under prescribed conditions, or a wildfire. Society is faced with deciding to accept periodic episodes of low concentrations of smoke from managed fires or heavy doses from wildfires. Reduced emission restrictions for wildland management activities will be necessary if fire is to be allowed to play its natural role in Mediterranean ecosystems.

Looming in the immediate future is climate change. As Westerling et al. (2006) have pointed out, climate change is already affecting fire regimes in the western US. Fires are starting earlier, lasting longer, becoming larger, and burning with greater severity. This pattern is repeating in the Sierra Nevada and southern Cascade Mountains of California and Nevada (Miller et al. 2008) and in Yosemite (Lutz et al. 2009). Managing landscape level fire regimes will become increasing important but difficult under these changing conditions.

The success of fire management in Mediterranean climate regions is contingent upon society's ability and willingness to keep fire as an integral part of these ecosystems. Protected areas are, perhaps the last refuge for conserving fire and landscapes. Strong natural fire programs are extant in the United States, and prescribed fire is being applied at the landscape level in South Africa and Australia. Opportunities for similar programs exist in Europe, northern Africa, and South America. Managers will need to work closely with scientists to ensure that fire programs are ecologically sound and operationally safe.

# Chapter 4
# Mapping Fire Risk in Mediterranean Ecosystems of California: Vegetation type, Density, Invasive Species, and Fire Frequency

**Susan L. Ustin, David Riaño, Alexander Koltunov, Dar A. Roberts, and Philip E. Dennison**

**Abstract** California ecosystems and climate have characteristics that promote to wildfire, particularly in the dry late summer and fall seasons. Over recent decades, fire severity and number of fires has increased. In many cases, the changing fire regimes have been concurrent with the spread of invasive annual grasses into shrub and woodland habitats that provide dry fuel in the late summer/fall season. Remote sensing data, especially high spatial resolution airborne hyperspectral data has contributed to better mapping of vegetation types and characteristics and assessment of the biophysical condition of the vegetation, mostly related to drought status. These data can provide inputs to improved wildfire risk models. The temporal 1 day and 8 day resolution of the weather satellites contributes information on vegetation dynamics, particularly MODIS provides spatially distributed changes in canopy water content as the vegetation in these fire prone ecosystems dries and fire risk increases. Lastly, we describe a new multitemporal classifier to monitor early detection of near real-time fire ignitions using the half-hourly geostationary satellite.

## 4.1 Introduction

The California Floristic Province defined by the Mediterranean-climate region is generally identified as the area west of the Great Basin, Mojave and Colorado deserts, extending from southern Oregon to northern Baja California (Keeley 2001). About 80% of California, mostly within the Mediterranean climate region, is classified as forest (125,242 km$^2$) and rangeland (230,670 km$^2$). These landscapes include a diverse biota, with a high proportion of rare and endangered species. The

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Floristic Province encompasses more than 4,400 plant species, about half being endemic (Raven and Axelrod 1978) and a quarter being invasive (Rundel 2000).

California experiences an unusually strong Mediterranean climate, due its annual drought that can last for three to ten months. Severe multiyear droughts have occurred in the late 1970s, late 1990s to early 2000s and California is currently in its third year of below average rainfall. Drought intensity and duration are major factors in wildfire risk. Interannual rainfall is highly variable, influenced by both by El Niño/Southern Oscillation (ENSO) and Madden Julian Oscillation (MJO) (Jones 2000). The El Niño (warm phase) alternates with the "normal" phase and the cold phase La Niña (Philander 1998). The three to seven year cycles mean that years of abundant plant growth water availability is the primary factor controlling canopy development and productivity (Miller et al. 1983; Rambal 2001) are followed by years of drought, building up fuel concentrations that support catastrophic wildfires. Further, the effects of ENSO are not uniform across California as El Niño years are correlated with higher than normal winter precipitation over most of the State, but are strongest and most consistent in southern California and weakest in northern California (Castello and Shelton 2004), which has contributed the more severe fire risk in southern California. Since the 1970s, ENSO events have become more extreme (Kumar and Hoerling 1998), consistent with other global climate changes (Timmermann 1999). The climate warming and reduced snowpack (Knowles and Cayan 2002) combined with well intended but ecologically disastrous fire suppression in forests over the past century, has left the state more vulnerable to large uncontrolled catastrophic wildfires.

In the past 30 years California has also nearly doubled its population density from 49 to 93 people/km$^2$. Accidental and arson fires, combined with stronger droughts in recent years have led to an increase in the most severe classes of fires (Fig. 4.1), which are changing fire regimes in these systems (Syphard et al. 2007). The earlier start combined with a prolonged fire season has virtually eliminated a "non-fire season" period as wildfires now occur throughout the year. Additionally, more recursive severely damaging fires have caused land degradation and possibly

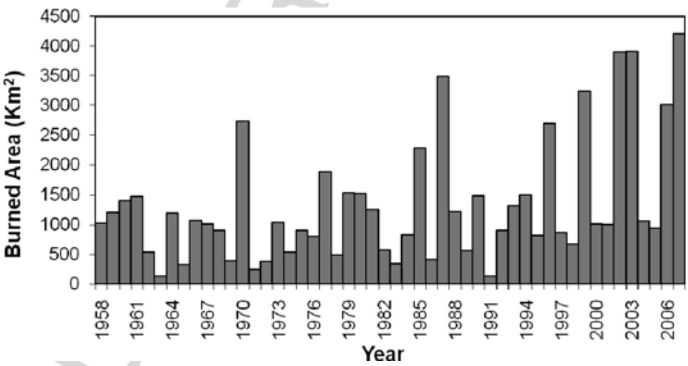


**Fig. 4.1** Burned area by year in California from 1958 to 2008. Data from CalFire

permanent shifts in ecosystem patterns (Syphard et al. 2007). Often these changes are accompanied by expanded dominance of invasive plant species, which may be facilitated by the new fire regime, particularly if the new species change the functionality of the ecosystem (Drake et al. 1989; Pausas et al. 2004; Vitousek 1986).

Past history, current trends, and climate change simulations indicate that California is likely to have more extreme weather in the future and could face periods of even more extended drought (Hayhoe et al. 2004). Extended multiyear droughts are recorded in the geologic record (Everett 2008). Most current GCM predictions indicate that California will have significantly warmer winters and summers, enhanced ENSO events, with longer periods of annual drought, however the sign and magnitude of precipitation predictions remain much less certain (Hayhoe et al. 2004; Lenihan et al. 2003). Such sustained changes will alter the distribution of California ecosystems, likely extending grasslands into chaparral and forest ecosystems, which may in turn further alter California's wildfire regime.

## 4.2 Environmental Components of Wildfire Risk

Fire risk can be defined as a product of fire occurrence probability and expected impacts (Bachmann and Allgöwer 2001). Based on this definition, an area can be considered to have high wildfire risk if the probability of fire is high and the expected impacts of fire are large. Environmental and societal factors contribute to make California one of the highest wildfire risk areas globally, as illustrated by a number of recent, highly destructive fires (Keeley et al. 2004). Numerous environmental factors favor frequent, highly destructive wildfires including its Mediterranean climate, rugged terrain, fire adapted vegetation types, complex biogeographic mosaics often with high vegetation density. Fire risk is further enhanced by dense vegetation along the wildland-urban interface, leading to increased in ignition sources.

Overall, Mediterranean climate of California is characterized by cool, moist winters and hot dry summers. This climate pattern promotes rapid growth of vegetation in the late winter and spring, when temperatures are mild and moisture is plentiful, followed by gradual drying as soil moisture becomes depleted. Regional climate is modified by topographically-induced microclimates, resulting in extensive rain shadows on the interior sides of the north-west oriented mountain ranges and significant environmental gradients in temperature and moisture due to solar radiation differences. The net result is a complex mosaic of vegetation with variable susceptibility and response to fire that accumulate fuels when moisture is plentiful, and generate high loads of dry fuels in the late summer and fall.

Fire is a product of static and dynamic factors that influence the probability of ignition and rate of spread (Countryman 1972; Moritz et al. 2005; Pyne et al. 1996). The environmental factor that contributes to the most extreme fire behavior in California and the most damaging fires is the topographically-induced Santa Ana winds, localized in southern California. Santa Ana winds are generated by large scale pressure patterns, in which high pressures in the interior and low pressures long

the coast create strong gradients that lead to high winds and adiabatic heating. The fall and early winter timing of the Santa Ana winds is important, due to the differential cooling between the coast and interior, at the same time that fuel moisture is typically at its lowest (Raphael 2003). The most costly fires in California history, including the fire storms in 2003 and 2007, have occurred during fall Santa Ana winds (Keeley et al. 2004; Westerling et al. 2004). In Northern California, topography also plays a key role in the manner in which it modifies fire spread and redirects fire generated winds. Ignition sources also vary within the state, with a majority of human-induced fires occurring in shrublands and grasslands. Lightning is the only significant source of ignitions in more forested regions, especially at higher elevations and in the northern parts of the state (Keeley 1982). Due to the importance of anthropogenic ignitions, the presence of roads, houses or other developed infrastructure is often the best predictor of ignition risk.

The major fire prone ecosystems in the state include extensive, relatively low biomass grasslands, intermediate biomass semi-arid shrublands (chaparral and desert shrublands) and open canopy woodlands and high biomass closed conifer forests at higher elevations (Sugihara et al. 2006). The type of vegetation present within a region is largely a product of available soil moisture, disturbance history, and temperature. Grasslands are primarily concentrated in regions where soil moisture is limiting for some part of the year, often on relatively low elevation shallow slopes or sites having frequent disturbance. Shrublands occur at more intermediate elevations, typically occurring on steeper slopes while forested ecosystems are restricted to regions of higher available soil moisture and lower temperatures, typically at higher elevations or within riparian zones.

Wildfire fuels include downed debris, such as duff or fine litter, standing dry materials such as senesced grass, and fine leaves and stems. The fuel moisture content of these litter fractions is related to the atmospheric humidity and equilibrium hydration level. The proportions and timing at which each of these components is susceptible to ignition and can carry a fire varies between ecosystems. For example, grasslands typically consist of low fuel loads that dry earliest in the summer season and thus propagate low temperature, rapid fires (Anderson 1982). Shrublands, such as chaparral, typically propagate crown fires and become susceptible to extreme fire events when fine live fuel moisture (leaves and stems) decreases below 77% (Dennison et al. 2008). The hydration extent of live fuel moisture is related to moisture, temperature, and wind speed, but also dependent on active stomatal regulation by the plant. Moderate to low intensity surface fires in forests are restricted to litter and duff layers, but can under more extreme wind conditions or given extensive ladder fuels, propagate to the crown where they are far more damaging. The importance of crown fires, either in shrublands or forests, and the role of fine fuels as a medium for fire propagation, makes live fuel moisture particularly important as a measure of fire danger in California ecosystems.

Seasonal changes in available soil moisture and the seasonal nature of extreme wind events, such as the Santa Ana's, tend to concentrate the greatest number and largest fires in the late summer and early fall (Raphael 2003). However, because of the important role of climatic factors in controlling fire in the state, there is

considerable inter-annual variability, with the most extreme fire years occurring when live fuel moisture is unusually low in combination with one or more Santa Ana wind events. Fire incidence tends to be low in either above average moisture years, such as 1998 and 2005, or dry years with no Santa Ana winds. While a large number of fires do occur earlier in the year between June and August, these are typically smaller, although there are exceptions such as the 2007 Gap fire or the large number of fires that burned in 2008 that were concentrated in Central and Northern California and which were primarily started by lightning.

## 4.3 Detection of Changing Wildfire Frequencies

### *4.3.1 Recent Changes in Fire Size*

Analysis of fire statistics from the California Department of Forestry and Fire Protection (CalFire) indicates that the size of large fires has increased over the past three decades. Fires in the CalFire database from 1958 to 2007 were separated into two 25 year periods and compared. For each period, fires were rank ordered from largest to smallest fire, and fire size was plotted against rank (Moritz 1997). The trend 1983–2007 is shifted to larger fires, compared to fires for 1958–1982 (Fig. 4.2).

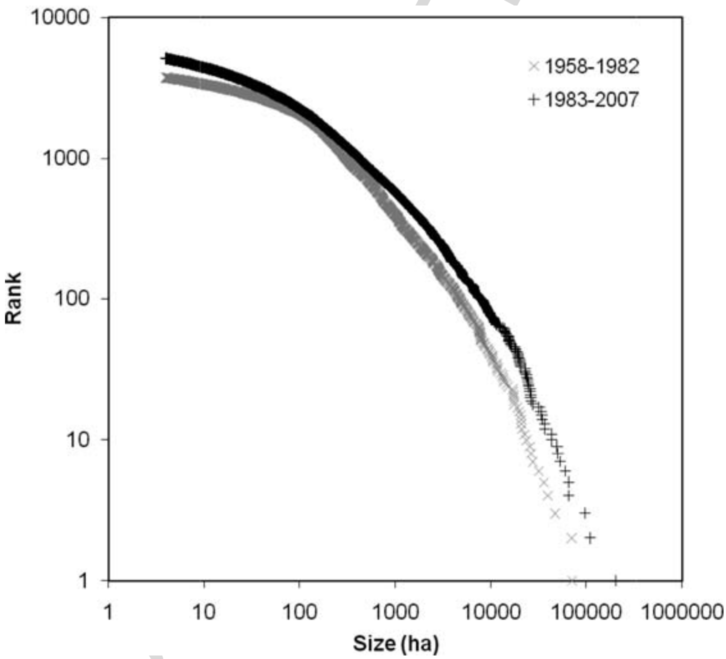


**Fig. 4.2** Fire size versus rank (from largest fire to smallest fire) for fires in the CalFire database, from 1958 to 1982 and 1983 to 2007

Statistics for individual fires demonstrate an increase in the occurrence of so-called "megafires". Of the 20 largest fires since 1958, 15 have occurred since 1983 and 9 have occurred since 2000. The three largest fires in the CalFire database – the 2000 Biscuit, 2003 Cedar, and 2007 Zaca Fires – all occurred since 2000. Although the occurrence of large fires in California has dramatically increased, it should be noted that these statistics document fires extending over a wide range of ecosystems that do not have equal probability of large fires. For example, the Cedar and Zaca fires were predominantly chaparral fires, while the Biscuit Fire was predominantly a forest fire that straddled the California-Oregon border. This increase in large fire occurrence may miss important but more subtle changes in fire occurrence in individual ecosystems.

#### 4.3.1.1 Fire Ignition

The National Interagency Fire Center (NIFC) monitors the regional number of ignitions and area burned since 2007. NIFC statistics for the Northern and Southern California regions indicate that in California, human ignitions occur almost six times more often than lightning ignitions (Table 4.1). Southern California experiences less summer thunderstorm activity than northern California, and as a result human ignitions occur more than 10 times more often than lightning ignitions. The disparity between human and lightning-caused fires is smaller for average annual area burned, especially in northern California.

**Table 4.1** Average annual number of ignitions and area burned for Northern and Southern California, using statistics from the National Interagency Fire Center from 2001 to 2007

| | Ave. annual ignitions | Ave. annual ignitions |
|---|---|---|
| Northern California | (2001–2007) | (ha) |
| Lightning | 840 | 30,795 |
| Human activity | 3,148 | 42,541 |
| Southern California | | |
| Lightning | 391 | 18,025 |
| Human activity | 4003 | 145,187 |

The wildland-urban interface (WUI) is an important source of ignitions in California. Syphard et al. (2007) examined relationships between fire frequency and WUI variables in California. They found that the number of fires per square kilometer was highest at intermediate population densities. Other variables that explained some of the spatial variation in fire frequency included distance to WUI, fuel type mixtures, and housing density.

## 4.4 Remote Sensing Detection of Wildfire Danger and Risk

Before the use of remote sensing data, wildfire danger and risk assessment required extensive field campaigns to estimate risk. In a pioneering work Show and Kotok (1929) generated a 6,108 ha vegetation map in northern California to assess fire

control that required 10 years of field work. The value for fire risk assessment was limited because the concept of fuel types had not yet been developed (Hornby 1935). This work preceded the availability of aerial photography for forest mapping which began to be used in the 1930s and obviously, preceded remote sensing capabilities by decades (Adams 1965).

With remote sensing technology still maturing, Salazar (1982) generated a fuel type map in northwestern California with clustering and unsupervised classification of Landsat Multispectral Scanner (MSS) that was validated with color aerial photography and field data. She employed the National Fire Danger Rating System (NFDRS) (Deeming et al. 1978) and the US Forest Service's Northern Forest Fire Laboratory (NFFL) fire behavior model, also known as Behave (Albini 1976; Anderson 1982). This non-spatial model uses inputs of fire fuel type, topography, and weather data to predict fire behavior. There are two fuel type classification systems most widely used in the USA, one from the wildfire danger point of view and the other in terms of wildfire behavior. This study was one of the first to map fuel types based on remote sensing data, and set the basis for the generation of operational products for wildfire danger and risk assessment.

The California Department of Forestry and Fire Protection′s Fire and Resource Assessment Program (FRAP, frap.fire.ca.gov) produces an operational fuel type map for the entire state of California (latest version 2005) with 30 m pixels, adapting the vegetation map: Classification and Assessment with Landsat of Visible Ecological Groupings (CALVEG). This map was built using a hierarchical classification scheme with information about species, crown cover, and crown size from Landsat Thematic Mapper (TM) in unsupervised and supervised classifications. It was validated with color aerial photography and extensive field work. CALVEG, together with ancillary information, such as slope, aspect, elevation, watershed boundaries, and fire history, was "cross-walked" into 13 standard NFFL fuel types plus 7 customized ones. Chaparral fuel types dominate the coastal mountains in southern California, while forest fuel types predominate in coastal mountains of northern California and in the Sierra Nevada Mountains and grass dominated fuels surround the foothills of the Central Valley and occur in smaller patches within the forest and chaparral types. The FRAP methodology was initially developed by Sapsis et al. (1996) for the Sierra Nevada Mountains, CA.

New remote sensing techniques to improve the NFFL fuel type maps have been experimentally tested in Yosemite National Park, CA using multitemporal Landsat TM data (Van Wagtendonk and Root 2003). Researchers applied unsupervised classification on multitemporal Normalized Difference Vegetation Index (NDVI) to capture the phenological changes in fuels, where fuel types were mainly based on aerial photography, and they validated with field data. Another novel approach was carried out in the Santa Barbara area where fuels were mapped using Multiple Endmember Spectral Mixture classification Analysis (MESMA) with NASA's airborne hyperspectral sensor AVIRIS (Dennison and Roberts 2003a, b), and with the satellite hyperspectral sensor, Hyperion (Roberts et al. 2003). The authors applied a site specific fuel type classification for these chaparral communities. The higher spectral resolution of hyperspectral imagers significantly improved accuracy of discrimination between species, which can be used to map different fuel types. Lidar

is the best-suited remote sensing instrument to map fuel structure, by providing a direct measurement of the vegetation height and the three-dimensional arrangement of fuel elements. Lidar data have been experimentally tested in the Sierra Nevada Mountains (Hyde et al. 2005) as part of the project "Validation of Crown Fuel Amount and Configuration Measured by Multispectral Fusion of Remote Sensors" supported by National Aeronautics and Space Administration (NASA) and the Joint Fire Science Program (JFSP). Within the scope of the project specific fuel type properties, such as canopy bulk density and canopy base height were accurately estimated from Lidar and validated based on extensive field data (Hyde et al. 2005; http://jfsp.nifc.gov/projects/00-1-3-21/00-1-3-21_final_report.pdf ).

Live fuel moisture content (FMC) and dead fuel moisture (DMC) are other wildfire danger and risk components, together with fuel types and fuel structure have been traditionally measured by destructive sampling. Dead fuels, generally standing woody debris and down woody debris, located under the vegetation canopy, are generally more closely related to meteorological indexes (Burgan et al. 1998; Camia et al. 2003) than remotely sensed ones as fuel hydration depends on atmospheric humidity.

The live FMC component of fire risk is highly dynamic between wet and dry years (in response to strong El Niño and La Niña cycles) and seasonally in response to summer drought, which can change quickly over short periods during drying weather, such as from Santa Anna winds. One of the first field protocols for live fuel moisture was developed for Californian chaparral (Countryman and Dean 1979). This protocol set the basis for the current US Forest Service National Fuel Moisture Database (http://72.32.186.224/nfmd/public/index.php). Field samples are collected, every two weeks over the dry season, mainly in central and Southern California. Although field samples are collected systematically by this and other agencies, data are inadequate to develop response plans due to the difficulty in obtaining sufficient samples over a realistically wide spatial extent in a brief period of time, while maintaining consistency through time. Remote sensing represents an alternative methodology to measuring FMC.

Relative greenness, temporal variation in NDVI obtained from NOAA-AVHRR, have been related to FMC and validated for Nevada and California (Burgan and Hartford 1993; Burgan et al. 1998) to provide, together with meteorological data, a Fire Potential Index for the USA.

In Southern California, other vegetation indexes that take advantage of water absorptions in the shortwave infrared (SWIR) region of the spectrum (1,500–2,500 nm) provide better FMC estimates than NDVI. One example is the Normalized Difference Water Index (NDWI) (Dennison et al. 2005a) calculated from MODIS. Zarco-Tejada et al. (2003) used a combination vegetation indexes trained using a radiative transfer model to predict canopy water content, while Dennison et al. (2005a) included the visible infrared index, VARI, in a multiple regression model, to accurately predict FMC (Peterson et al. 2008). VARI does not measure SWIR water absorption bands, but seems to be less sensitive to vegetation cover and background variation (Stow and Niphadkar 2007; Stow et al. 2005, 2006). Schneider et al. (2008) calculated relative greenness based on VARI to build, together with a fuel type map and meteorological data, a fire potential index for southern California.

FMC also considers changes in dry matter content, which is masked in the optical remote sensing signal when leaves have high water content (Riaño et al. 2005). Canopy water content (CWC), is more closely related to remote sensing data than the Equivalent water thickness (EWT) which requires multiplication by leaf area index (LAI) to estimate CWC. CWC estimates the total amount of water in the canopy per unit ground area, and can be transformed to FMC by dividing by dry biomass. The dry matter content has less variation than CWC, since seasonal and even inter-annual variation in dry matter content is less dramatic than variation in hydration. Research in California pioneered estimation of canopy water content (CWC) from AVIRIS (Roberts et al. 1997b; Serrano et al. 2000; Ustin et al. 1998). Contiguous, narrow spectral bands makes this instrument suitable for the direct CWC estimation due to discrimination between water vapor and liquid water absorption features (Green et al. 1991; Green et al. 1993; Roberts et al. 1997b). AVIRIS CWC estimates in the Santa Monica Mountains of southern California were combined with meteorological weather indexes that account for soil moisture to improve relationships with field measured FMC (Dennison et al. 2003). In Los Angeles County, CWC and other vegetation indexes from AVIRIS were also correlated to FMC and cross-calibrated with MODIS (Roberts et al. 2006a).

AVIRIS CWC was used to validate CWC estimates from MODIS (Trombetti et al. 2008) following a modeling exercise to test these relationships (Cheng et al. 2006). The latter method was based on inversion of a linked canopy radiative transfer model, the Prospect-Sail-H models. Vegetation indexes based on the modeled canopy reflectance were used in the inversion of the RT model to obtain CWC, which were applied to MODIS using an artificial neural network to optimize running the algorithm on a large number of pixels. An example of the MODIS results for the years 2000–2007 are shown in Fig. 4.3, where CWC estimates for the week before the San Diego wildfires that started on October 21st, 2007. The year 2007 was drier than average for the same period time in the two previous years and the CWC for the same calendar date varies significantly between years.

## 4.5 Invasive Species and Wildfire Intensity and Frequency

Keeley et al. (2005) reported that in the first five years after wildfire in southern California shrublands, 75 species, mostly European annuals, invaded the burned areas. These species can increase the fire frequency, ultimately changing the species composition and functionality of these ecosystems. When fires are combined with grazing there is even greater pressure toward alien invasion (Murphy and Leonard 1974). High fire frequency has contributed to conversion of shrublands and woodlands to annual grasslands dominated by species of Mediterranean Basin origin throughout the Coast Ranges and the Sierra Nevada foothills (Keeley 2001). Such disturbed landscapes are readily invaded by Mediterranean annuals, which comprise nearly 60% of the California's invasive flora (Murphy and Leonard 1974; Raven 1977). Although dominated by invasive annuals, tree species like Australian eucalyptus (Eucalyptus globules) also contribute to changing fire regimes.

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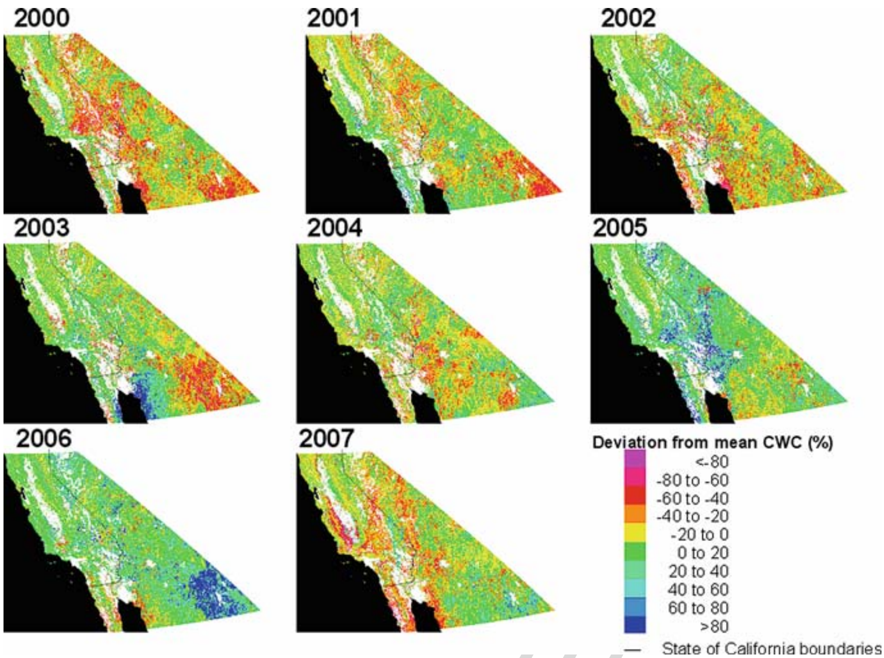


**Fig. 4.3** Percentage deviation for each year from the mean CWC (2000–2007) calculated for the week preceding the San Diego wildfires which began on October 21st, 2007. CWC was calculated from MODIS Terra 8 day composites (MOD09A1) version 5, October 8–15th, 2000–2007 using the method of Trombetti et al. (2008). Only natural vegetation pixels with valid CWC estimates for all years were considered*

Additionally, more recursive severely damaging fires are occurring during droughts in recent years which have caused land degradation and possibly permanent shifts in ecosystem patterns (Syphard et al. 2007). Often these changes are accompanied by expanded dominance of invasive plant species, which may also interact with the fire regime, particularly if a change in growth form, biomass, and resource use is involved (Keeley 2006; Mooney and Cleland 2001). California is remarkably rich in biodiversity due to its complex terrain, soil diversity and climate. Among the biologically richest are the sclerophyllous vegetation dominated landscapes that are particularly prone to wildfires, such as chaparral and mixed woodlands and forests. California also has an unusually large number of invasive plant species, a function of the same forces that drive the numbers of native species that create the reticulated mosaic of habitats. The extensive history of disturbance from logging, grazing and agriculture, have facilitated the spread of invasive plants, many of which have changed the ecological functioning of the systems they have invaded. Species like starthistle (Centaurea solstitialis) and Asian Mustard (Brassica tournafortii) have invaded annual grasslands, pampas grass and jubata

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*For colour version of this figure, please refer Colour Plate Section.

grass (Cortaderia jubata) have invaded coastal chaparral communities, eucalyptus (Eucalyptus globulus) woodland and forest communities, while Tamarisk (Tamarix spp.), giant cane (Arundo donax), and common cane (Phragmites communis) have invaded riparian zones, all affecting the density of vegetation, fuel load, hydrological processes, timing of seasonal growth, and hence, the fire regime of the invaded communities.

In recent years, several publications have demonstrated the potential to map invasive species distributions using high spatial resolution hyperspectral data to identify them by their spectral properties. Among the expanding list of species mapped using these data are iceplant, eucalyptus, and jubata grass (Underwood et al. 2003), yellow star thistle (Miao et al. 2007) and arundo (Ge et al. 2008). Using the MESMA approach, Roberts et al. (1998) showed for the first time it was possible to make detailed species and community maps of chaparral ecosystems. Recently, Andrews and Ustin (2009a, b) show these data can be used to predict the spatial spread of an invasive species, pepperweed and to relate its expansion rate to climate conditions.

## 4.6 Toward Early Detection of Wildfire Ignitions

Timely and accurate information about ignition events is necessary for cost-effective and accurate fire-fighting responses. Earlier detection often leads to smaller fire size, and therefore reduces the probability of fire escape (Hirsch et al. 1998), final fire size, cost, and risks to fire response crews. Presently, the initial identification of wildfires in California is primarily by passive human observations (e.g., notification by the general public, commercial airline flights, fire lookout stations, etc.), by aerial reconnaissance during periods of high fire danger or ignition potential (e.g., during Santa Anna winds or lightning storms). The non-systematic, infrequent, and/or geographically localized nature of ignition monitoring methods can lead to substantial latency before ignitions are detected. For instance, in the 2008 fire season, California experienced thousands of simultaneous fires due to lightning strikes. Under these conditions, detection by human observers was much less effective due to widespread smoke, and as a result reports were incomplete and arrived with significant delays.

Under these circumstances, satellite observations using thermal infrared are receiving increasing attention as a potential low-cost systematic means to promptly detect wildfires over large areas. While large active fires have been successfully mapped from space for decades, the corresponding fire detection products have not significantly reduced fire latency. Measurements by polar-orbiting sensors (AVHRR, MODIS) are spaced by intervals of six hours, and therefore are only suitable for early alarming in the most scarcely populated areas. Geostationary images like GOES, although available at 15-min. time steps, but have coarse spatial resolutions, leading to small-magnitude thermal anomalies at the pixel level, thus creating significant challenges to developing an effective fire detection algorithm.

Today's most prominent fire detection methods, the GOES Wildfire Automated Biomass Burning Algorithm (WF-ABBA) (Prins and Menzel 1994) and MODIS-FIRE (Giglio et al. 2003) detect fires by identifying anomalously large values in two brightness temperature bands, the 4-$\mu$m band and the difference between this band and the 11-$\mu$m band. The performance of contextual methods is inversely related to the natural background variability which can reduce sensitivity to thermal anomalies and lead to high false positive rates. California, with its fine scale mosaic of vegetation types, topography, and variable soil conditions produces substantial error in these methods.

In contrast to the fire monitoring role of contextual methods, an early fire detection system minimizes the time to initial detection. Using multi-temporal thermal infrared data to detect fires as a class of anomalous temporal changes has been demonstrated by (Koltunov and Ustin 2007). Using multitemporal MODIS data they demonstrated that thermal anomalies could be accurately detected from changes due to the environmental dynamics of normal background evolution, as mathematically and physically derived by Koltunov et al. (2009). Ongoing experiments with GOES data have shown that even in densely populated areas of California, ignition reports from conventional sources are often received long after the fire can be detected by the GOES imager data at 15-min intervals (Table 4.2 and Fig. 4.4). Further improvements could be achieved by correcting satellite images for misregistration, improving cloud detection, and intelligently combining multi-temporal and contextual detection algorithms. These developments in collaboration with fire management agencies will improve fire response and planning.

**Table 4.2** Examples of reduction in detection latency for several major California fires during 8/13–9/03, 2006. Listed are only large (final size >2 ha) wildfires that started in Central California during 8/13–9/03 in 2006, with reported start time. Fire data provided by CALFIRE (California Department of Forestry and Fire Protection)

| Fire Name and Start Date | Time of initial report or estimated start | GOES EFD first detection time | Estimated reduction in detection latency assuming 15-min processing + delivery lag | Comment |
|---|---|---|---|---|
| Marysville-Dobbins, 8/16 | 13:05 | 11:10 | 100 min | |
| Rollins, 8/19 | 14:38 | 14:00 | 23 min | See also Fig. 4.3 |
| Boundary, 8/21 | 15:00 | 13:59 | 46 min | Previous image available at 13:30 |
| Sand Flat 9/03 | 14:30 | 13:59 | 16 min | Previous image available at 13:30 |

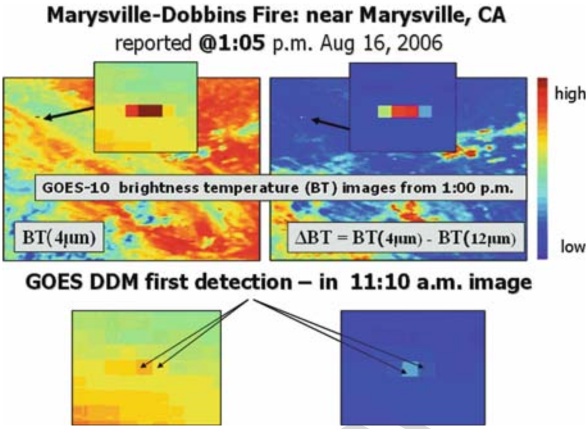


**Fig. 4.4** Example of early detection of a real wildfire by applying two multitemporal Dynamic Detection Model-based detectors to geostationary GOES-10 Imager data (see also Table 4.1)*

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## 4.7 Conclusions

California has experienced severe wildfires in recent years that appear to be increasing in frequency and intensity. These events are driven by the interaction of physical factors like those imposed by climate warming superimposed on the highly variable interannual weather conditions resulting from ENSO and MJO phases, by biological factors, especially the mosaic of fire adapted grass, shrub, and forest ecosystems in California, and by human factors including expansion of urban structures into wildlands, and both arson and accidental ignitions during severe drought periods. Increasingly, the climate change driven extension of the summer drought in California, combined with population growth in areas most likely to experience wildfire, e.g., the Coastal and Transverse mountains around Los Angeles and San Diego, indicate that these problems are likely to worsen in the coming decades. For these reasons and the prohibitive cost of fighting fires once started, require improved methods to identify early warning for fire risk and for early detection of fire ignitions to support quick response. In recent years, many new remote sensing methods have been proposed to improve assessment of wildfire risk and earlier detection of wildfires. We have provided a few examples from this literature to illustrate the types of information that can now be produced by airborne lidar sensors to estimate biomass and leaf area. And by optical sensors ranging from high spatial and spectral resolution airborne hyperspectral imagers to multispectral satellite instruments with high temporal frequency like MODIS and GOES that can capture dynamic changes in physical properties of vegetation like canopy water content and live fuel moisture that can inhibit or promote the rate of spread of wildfire or can be used rapidly to detect thermal anomalies within minutes of fire ignitions.



*For colour version of this figure, please refer Colour Plate Section.

# Chapter 4

| Q. No. | Query |
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# Chapter 5
# Fire Danger, Fire Detection, Quantification of Burned Areas and Description of Post-Fire Vegetation in the Central Area of Chile

**Roberto Castro Rios and Dante Corti González**

**Abstract** Since Chile is a large country with Mediterranean climate (Central Zone) with important forestry and tourism activities, forest fires are one of the priorities of the Forest Service and Civil Protection, and it is also an issue widely investigated by various authors. In fact, Quintanilla and Castro (1998) mentioned that despite the positive effects of fires, vegetable communities tend to degrade steadily in a long-term process as a result of fire, with an increasing presence of exotic over native species. In that context, the remote sensing technologies combined with occurrence data, forest fire characteristics, climate and human risk constitute the basis for modeling in geographic information systems (GIS) and decision-making with regard to detection, pre suppression, suppression and burned area quantification.

## 5.1 General Characteristics of the Mediterranean Central Zone of Chile

The administrative regions that are included in the Chilean Central Zone are Valparaiso, Metropolitana, Libertador General Bernardo O'Higgins and Del Maule (Fig. 5.1[1]). The area is characterized by the presence of mesophite vegetation, precipitations around 600 mm/year and average temperatures around 15°C. During summer, temperature reaches 34°C and rainfall is scarce. The topography is mountainous (Coastal) and increase the concentration of population in the cost border cities and the frequency in the communication routes, where most of the occurrence of fire are located.

The Region of Valparaiso, located north of the Central Zone, is characterized in geomorphologic terms by the presence of recent cross valleys, forming a tran-

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[1] Corporación Nacional de la Madera (www.corma.cl)

E. Chuvieco (ed.), *Earth Observation of Wildland Fires in Mediterranean Ecosystems*,
DOI 10.1007/978-3-642-01754-4_5, 

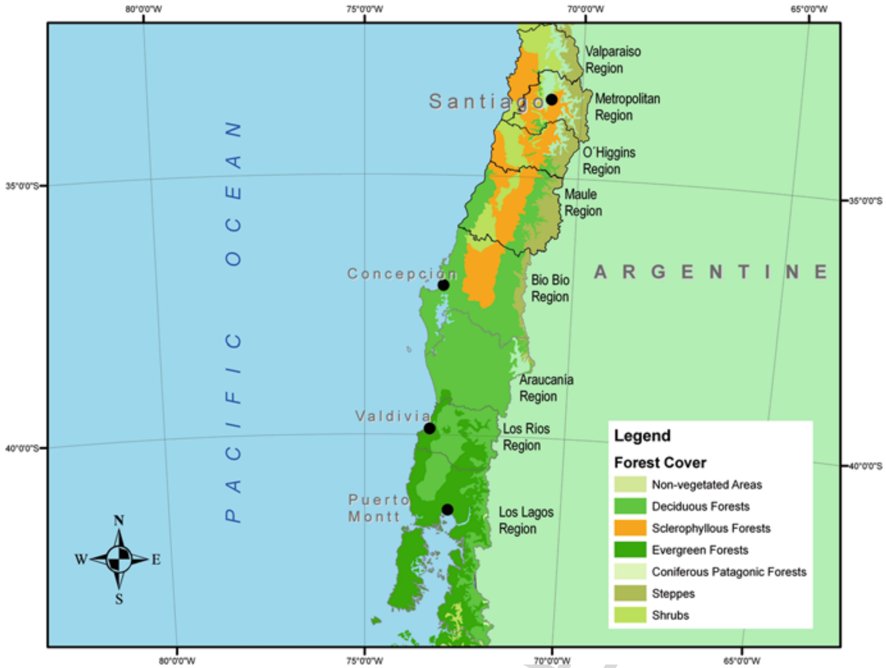


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**Fig. 5.1** Vegetation classes in the Mediterranean climate region of Chile, along with administrative regions*

sitional area, with fluvial-marine coastal plains and dune fields, sedimentation or alluvial plains, cords cross the Andean coastal system and so-called transitional semi basins., Strong variations of slopes and north exposition tend to favour forest fire occurrence. The region is located in the mesomorphic and Andina vegetation macrozones. The semi arid phytogeographic zone with predominance of xerophyl and mesophyll vegetation, shrubs and succulents and the sub humid zone with predominance of mesophyll vegetation, shrubs and arboreal, are present.

The Metropolitan region of Santiago is located to the East of the previous region and hosts 40% of the country's populations. This region is characterized by the cost mountain range, whose foothills penetrate into the central plains, as well as by marginal granite basins and recent alluvial backfill of the eastern slope. The strong topographic contrast difficults to access fire affected areas. Located at the mesomorphic and Andina macrozone and steeped in the Andean phytogeographic sub humid area with predominance of mesophyll vegetation, shrub and arboreal.

The next region, called region of Libertador General Bernardo O'Higgins, in regard of geomorphology, is identified by the presence of extensive coastal plains, alternating with cliffs areas. On the other hand, the cost mountain range is lower than the foothills of the Central Valley. Important volcanoes are located in this region. However, their heights are lower than those in previous regions. The region

*For colour version of this figure, please refer Colour Plate Section.

is located in the mesomorphic and Andean vegetation macro zones and the area belongs to sub humid phytogeographic zone with predominance of mesophyll vegetation, shrub and arboreal. The most representative's vegetation formations are *Acacia caven* steppe, scrubs and sclerophlyll species.

Finally, the Maule region present an increase of precipitation over the coastal zones and the central valley, from 700 to 2,500 mm/year in the surroundings of the Andes mountain range. Extensive coastal fields with presence of dune fields can be found in this region. The cost mountain range is weathered and diminished in height, characterized by a complex system of hills, while the central valley shows a broad development.

## 5.2 Fire and Impacts on the Mediterranean Area and Chile

The situation of forest fires in Chile is critical. Each summer both natural and planted forests suffer from important economic and ecological losses due to fires.

The average occurrence of forest fires in Mediterranean Chile between 1990 and 2006 averages 947 ha/year, which is 16% of all national forest fires, affecting a total of 6,075 ha/year (12% of the national burned surface). Each fire affects an average of 6.41 ha (INFOR 2006) (Figs. 5.2 and 5.3). AQ1

These numbers can be complemented with the ones published by CORMA, the association of forestry engineers (*Colegio de Ingenieros Forestales*) and the *Instituto Libertad y Desarrollo*, showing that each year an average of 5,200 forest fires are registered in Chile, affecting approximately 52,000 ha of shrub, natural and planted forests, causing a damage of US$ 50,000,000.

Apart from the economic damage, the negative impacts on the environment have to be considered, such as the loss of the vegetation cover – which is a protection against floods and erosion – of the civil infrastructure and quality of life, or even of human lives (INFOR 2003, Instituto Libertad y Desarrollo 2003). AQ2

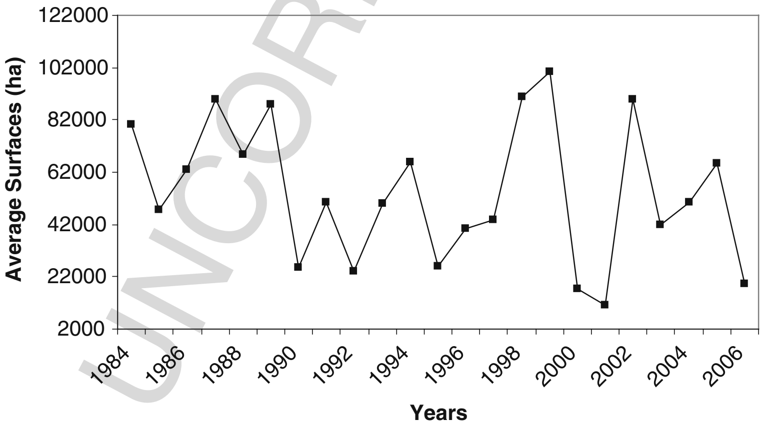


**Fig. 5.2** Annual average area affected by forest fires in Mediterranean Chile

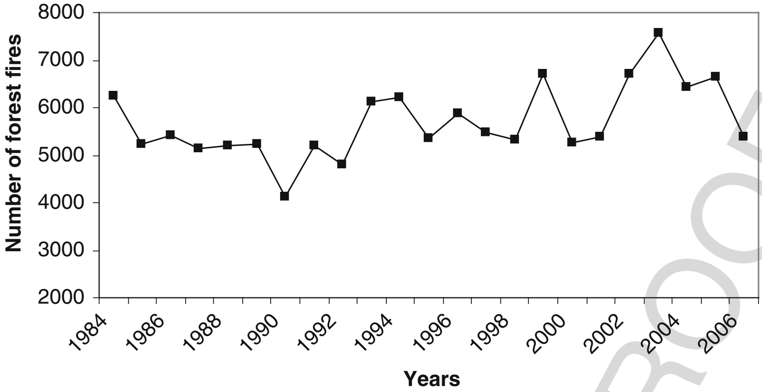


**Fig. 5.3** Average annual number of forest fires

In Chile the private forestry companies invest in the protection of their resources through fire fighting brigades and infrastructure. Also, the small and medium-sized landowners benefit from the subsidy of the government and the protective measures of the large companies who also protect the lands around or near their forests, in order to avoid that fires spread onto their lands or towards the populated areas.

On a national scale more than US$ 20,000,000 per year are invested in fire prevention and fire fighting. Out of this number, the private sector invests around US$ 14,000,000, while the government through CONAF (*Corporación Nacional Forestal*: www.conaf.cl), dedicates around US$ 6,000,000, which are mainly oriented to protecting the risk areas between Coquimbo and Magallanes, apart from renting land and air equipment (Instituto de Libertad y Desarrollo 2003).

The state protects the greatest surface, but at the same time has the least physical an economic resource for prevention and fire-fighting, as the private sector spends 36 times more than the public sector. Additionally it must be mentioned that only 15% of all forest fires take place on private property, and the annual rate of occurrence and damaged surface has been stable during the last 20 years, which gives rise to wondering about the efficiency of the preventive actions being taken by the state (Instituto de Libertad y Desarrollo 2003).

In this context the use of daily satellite indexes obtained from NOAA-AVHRR images, may help to reduce the negative impacts of fire through determining danger and risk indexes of forest fires by relating satellite information with the environmental variables of the resource. Fire danger is defined here as a quantitative and/or qualitative indicator that estimates the probability that a forest fires spreads on a certain surface at a certain point in time, based on the meteorological and natural conditions (inflammable materials, topography, etc.). Fire risk is defined in this chapter as the quantitative and/or qualitative indicator of the probability that an area may become subject to a source of ignition, being it natural or man-made. Occurrence of the ignition, with the purpose to estimate the probability that a forest fire starts on a certain surface at a certain point in time.

A forest fire can be defined like the propagation free, uncontrolled fire in forest ecosystems, caused by accidental, natural or intentional causes. Forest fires can be characterized as surface fires, which spread horizontally on surface affecting living and dead fuels that are at soil surface (up to 1–5 m tall). This kind of forest fire is more common in the Mediterranean area of Chile. Underground fire, starts superficially low and spread under the mineral soil due to the accumulation and compaction of the fuels. Crown fires start at a superficial level and become crown fires due to continuity of fuels. Crown fires are the most destructive, dangerous and hard to control.

In the Mediterranean area of Chile, as well as in the rest of the country, forest fires are mostly surface fires and human caused, being the highest occurrence related to urban-wildland areas of large cities and those of a major tourist attraction and the road network that interconnect major cities.

In the Mediterranean region of Chile, the main land uses affected by forest fires are shrub and grassland, representing more than 94% of the annually affected surfaces. The main causes and origins of forest fires are man-made (99%). Curiously, many children are responsible for fire ignition, because they want to see the fire fighters and CONAF fire brigade in action. More than 80% of all forest fires originate in the areas surrounding the cities and in wastelands (mainly settlings of the lowest income classes), and along the main highways of the country.

The main way of detecting a forest fire is from a CONAF watchtower network, accounting for 63% of the detection of all forest fires, and by the general public. In this region most of the forest fires originate between 2 and 4 pm, which corresponds to the time indicated by studies in Mediterranean regions in Europe (Fig. 5.4).

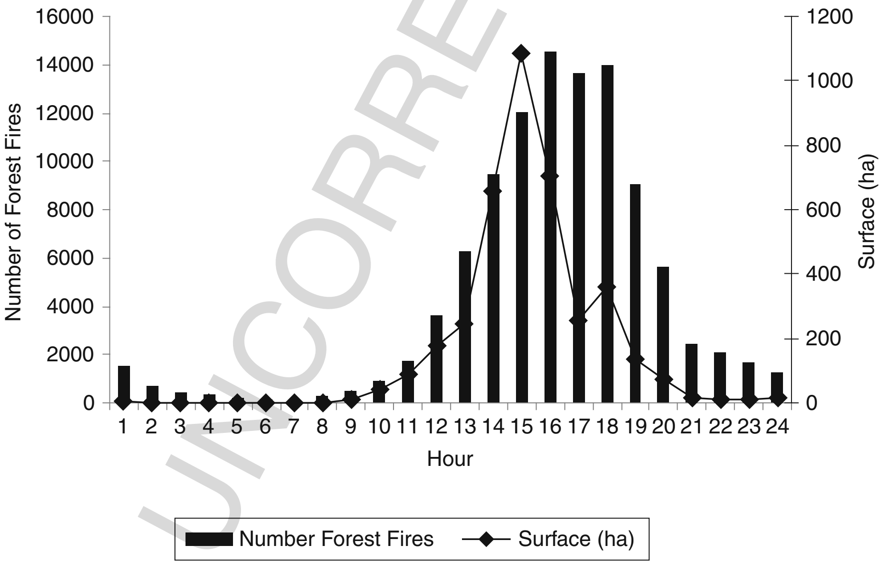


**Fig. 5.4** Number of forest fires and burned areas originated between 2 and 4 pm

## 5.3 Generation of Risk and Danger Indexes of Forest Fires from NOAA-AVHRR Images

Based on satellite information (vegetation indices, NDVI, and surface temperature), two forest fire indexes have been generated:

- Danger Index: Estimates de probability that a forest fires spreads from a determined area at a determined point in time, based on the meteorological and natural conditions (inflammable materials, topography, etc.)
- Risk Index: Occurrence of ignition, with the purpose to estimate the probability that a forest fire starts in a determined area at a determined point in time.

These indexes were validated and calibrated both through field information (grasslands and shrub), and the analysis of historic images from 1997 to 2005, and their relation to the occurrence and size of the forest fires (Table 5.1).

**Table 5.1** Danger index patterns

| Danger levels | Moisture content (%) |
|---|---|
| Extreme | <100 |
| Very High | 100–130 |
| High | 130–150 |
| Moderate | 150–160 |
| Low | >160 |
| Low | Areas with a high moisture level |
| Moderate | Areas of moderate danger, where a fire can easily be controlled. |
| High | Areas of high danger, where the occurrence of a fire affects the area partially or intermittently. The fire is moderately difficult to control. |
| Very High | Danger zones, where the occurrence of a fire can affect the area totally or partially. The fire is difficult to control. |
| Extreme | Areas of extreme risk, where a fire spreads quickly with a high probability. The fire is very difficult to control. |

Classification of the danger index according to the moisture content of the vegetation, with values between 1.35 (the lowest moisture content of grassland) and more than 160, corresponding to saturated shrub. These values have an inverted relation to the ignition danger of the material (Table 5.2).

Classification of risk index in degrees, with values between –1 and 1. The values are directly related to the surfaces that can be affected by a forest fire.

### 5.3.1 Determining and Calibrating the Risk Index

The functions used are modifications of the algorisms used by Chuvieco et al. (2004c). The results show that 60.1% of all forest fires in the 2006 season occurred within the “Low” range of the risk index, 26.9% within the “Extreme” and only 4 and 7.3% within the “Medium” and “High” range respectively. This may be

**Table 5.2** Risk index patterns (multiplied by occurrence factors of fires and the vicinity to cities)

| Risk levels | Degree (–1 a 1) |
|---|---|
| Extreme | >0.65 |
| High | 0.40–0.65 |
| Medium | 0.19–0.40 |
| Low | 0.08–0.19 |
| Zero | <0.08 |
| Zero | Very moist areas, far away from populated areas and roads. |
| Low | Low risk area, due to the high moisture degree of the vegetation. |
| Medium | Medium risk area, where the vicinity of populated areas and roads as well as the moisture and topography favor the outbreak of a forest fire. |
| High | Imminent risk area, due to the vicinity of roads and populated areas. The low moisture degree of the vegetation and the topography favor the outbreak of a forest fire. |
| Extreme | Maximum risk area, due to the vicinity of roads and populated areas. The low moisture content of the vegetation and the topography make an outbreak of a forest fire imminent. |

due to the human factor as a cause for forest fires, which in Chile reaches as much as 98%.

Even though the numerical relation between the risk ranges of fires and their occurrence does not give very precise results for the forecasts, it can be observed that 50% are within the higher ranges. This means that despite the high occurrence of fires in the low risk ranges, these fires do not affect great surfaces.

It is worth mentioning that there are different variables foreign to the system, which may alter the results of the index validations, such as incorrect georeferencing of the fires or of the images, which implies that fires are located outside the range they actually correspond to. Atmospheric or cloud contamination imply also severe problems to estimate correctly the fuel moisture content. The satellite images are the source of the indexes, so if they are of bad quality, or contain a lot of clouds, the indexes can be altered.

### *5.3.2 Determining and Calibrating the Danger Index*

In this index the range with the highest amount of occurrence was “Extreme”, with 40.2%, followed by “Very high” and “High” with 33.2 and 15% respectively. This shows that in this case the forecasts were quite correct. However, as in the case of the risk index, it was necessary to incorporate the data of previous seasons into the system and adjust the ranges of the danger index.

As the danger index estimates the probability that a fire spreads according to the vegetation conditions, the results of the validation of this index also were analyzed in relation to the total burned surface of all the fires within each range.

It was found out that the total burned surface was evenly distributed onto the different ranges of the index, with the exception of the “Low” range. This does not

mean that the system is giving false forecasts, because, as already mentioned, it is necessary to adjust the system based on the comparison of the historical occurrence of forest fires with the maps of each index, in order to achieve that the system produces more accurate forecasts.

The results of the index can also be affected by different external factors, such as the weather, as strong winds will cause a faster and uncontrolled spreading of a fire, which will lead to a greater burned surface. Another factor is the speed with which the fire brigades arrive, as it is much easier to extinguish a fire in its beginning, so a smaller surface will be affected.

## 5.4 Forest Fire Detection in the Mediterranean Area of Chile

The detection of forest fires is framed in the activities of fire pre-suppression, that are defined like the assembly of activities destined to organize, to prepare and to operate human resources and materials to detect and to fight forest fires. This it is a prior phase to fire extinction and without an adequate planning fire suppression would be inefficient. The pre-suppression includes activities such as:

Evaluation of Forest Fire Risk: aiming to establish different levels of alert of resources in response to current or forecasted weather conditions and rates of human risk.

Operation Central Organization: In the country, CONAF has implemented a total of 10 centres and 9 sub-centres between the IV and XII regions, in which the forest fires detection alarms are received. The regional offices are autonomous to attend to its resources of fire suppression, but they maintain permanently informed the National head Office of Coordination (CENCO), clerk of the department of Management of the Fire, which instructs and coordinates the displacement of the resources to national level.

Detection: Activity that is performed through: Mobile Land detection: having guards in small areas, system that is utilized for private companies for its properties. Fixed land detection: Using observation towers installed in places of good visibility. Aerial detection: Performed by light air craft, but this detection system is not widely used due to the high cost of implementation. Satellite detection: New technology of fast and practical application. Through specialized sensors thermal anomalies are discovered, it may be possible forest fires. Ideal system for far places of difficult access.

The more it used and most effective system of detection in Chile is that of the fixed terrestrial detection, with watchtowers installed in zones with good visibility, since which an observer maintains a permanent diurnal vision on a specific sector. In Chile, they operate on the order of 58 points of fixed terrestrial detection.

### *5.4.1 Spatial Detection Using MODIS Data*

The Remote Sensing has a great potential in the field of detection and monitoring forest fires, techniques that began to explore with the reception of data from the

first weather satellites during the 60 s, marked by the launch of the satellite TIROS-1 NOAA, and then with the NIMBUS program in 1964. Since 1978, the AVHRR sensor has been operating. Although it was not built for fire detection, this sensor includes a band in the middle infrared, which is suitable for active fire detection. The existing algorithms can be divided into two very broad categories: those of fixed thresholds and contextual (Justice et al. 2002; Fraser et al. 2003). The first relates to the more traditional methods used in detection and they are based on an absolute threshold determined empirically, while a contextual algorithm defines a threshold through an examination of the local statistics from the neighbour pixels. Contextual algorithms have been recently developed to try to improve the precision of detection (with respect to the fixed threshold).

The advent of satellite technology and specially expedited access to the data make it possible to use forest fire detection as a complementary tool of traditional field observation. A very useful tool in this regard is the Rapid Response System (RRS), developed within the MODIS (Moderate Resolution Imaging Spectrometer) program of NASA. This system was implemented in 2000 by the University of Maryland, the Goddard Space Flight Center (GSFC) from NASA and the Forest Service of the United States (USFS), as contribution to the Global Observation of Forest Cover/Global Observation of Landcover Dynamics (GOLD/GOFC). The main objective of the system available via the website is to provide rapid access to global information on fire and active thermal anomalies from the MODIS instrument which is aboard the Terra and Aqua satellites.

The RRS provides detected fires on top of seudocolour compositions of reflectance bands. The images are available locally within 3 or 4 h after the passage of the satellite. For the case of Chile, corresponds for TERRA between 13:30 and 15:40 UTC (10:30 a.m. and 12:40 p.m., in daylight summer time), and AQUA between 18:00 and 18:55 UTC (15:00 and 15:55 PM, in summer time). The images available directly (jpg format) are in the following combinations: Bands 143, with 0.25, 0.5, 1, 2 and 4 Km. resolution, for both satellites. Bands 367, with 0.5, 1, 2 and 4 Km. resolution for TERRA. 721 bands, with 0.5, 1, 2 and 4 Km. resolution for both satellites (Fig. 5.5). NDVI, with 0.25, 0.5, 1, 2 and 4 Km. resolution for both satellites. Land Surface Temperature, 1 and 2 Km. resolution for both satellites.

This information turns out to be useful to complement and to contrast the fires occurrence statistics in monthly, weekly form and for season, as well as to verify the daily detection of the fires occurred.

### 5.4.2 Detected fire events by the Rapid Response System

To better organized detected fires, a layout within ArcView GISTM was created, which incorporated the vector information base, from the topographic charts at 1:50,000 scale and image sub scenes defined by the PCI GEOMATICSTM software. All thermal anomalies were marked in a vector layer, associating each polygon (fire alarm) to an alphanumeric database with information derived from the MODIS scenes. The marked sites were compared with fire statistics collected by the Chilean

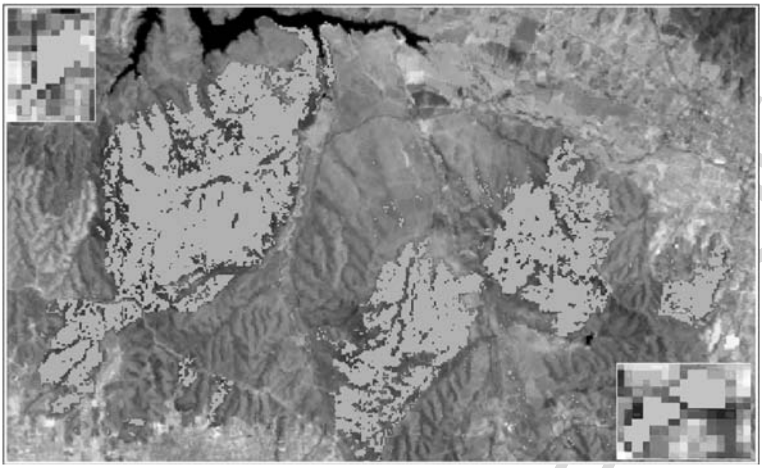

Fig. 5.5 Surfaces corresponding to the areas burned in the MODIS data

forest service (CONAF). The total number of thermal anomalies detected during the activation period of the system was 2,410, distributed by administrative region as follows: Valparaíso: 1.086; Region Metropolitana: 573; Region of Libertador Bernardo O'Higgins: 238; Region of Maule: 513. For the same period, according with records of occurrence of CONAF (named GEOREF), indicates that the region recorded 239 fires in Valparaiso, Metropolitan 150 Libertador Bernardo O"Higgins 138, Del Maule 103, a total of 630 fires.

The records of occurrence are determined, in order of making valid comparisons with the records of RRS, applying the following criteria:

- Fires started and controlled in time periods that do not correspond to the track of orbit of any of the 2 satellites.
- Fire developed in periods when there are no data for any satellite.
- Fires short-term, which have been initiated and extinguished between the tracks of the satellite.

The same way, the forest fires that are correctly detected by the sensor and the events that relate to false alarms are checked according to the location in the system GEOREF, in determining the date and time of the MODIS image, regardless of the date and time and the duration of the fire. For fires that were not detected, observations regarding the quality of the images for that day were included, considering that the active detection is the result of the different levels of saturation of both sensors.

Once records in the database from the National Forestry Corporation were edited and assessment of correctly detected fires and false alarms, we observed that for the entire study area the detection rate was relatively low (12%) (Table 5.3).

The total number of events detected by MODIS was 244.88 of which correspond to effective detections of forest fires, but they become 75 when discounting those fires detected in more than satellite orbit. The remaining 156 are thermal anomalies

**Table 5.3** Fires detected by RRS – MODIS

| Region | No Detection | Detection | Total | % No detection | % detection |
|---|---|---|---|---|---|
| De Valparaíso | 215 | 24 | 239 | 89.9 | 10.0 |
| Santiago. | 134 | 16 | 150 | 89.3 | 10.7 |
| Del Libertador B. O'Higgins | 123 | 15 | 138 | 89.1 | 10.9 |
| Del Maule | 83 | 20 | 103 | 80.6 | 19.4 |
| Total | 555 | 75 | 630 | 88.1 | 11.9 |

**Table 5.4** Forest fire detected by MODIS

| Events detected | Nº Events | % Events |
|---|---|---|
| Efective detection | 88 | 36 |
| False alarms | 156 | 64 |
| Total | 244 | 100 |

that do not correspond to forest fires, like agricultural burns or other heat sources (Table 5.4).

The majority of fires found were around 1 ha. From the total number of anomalies detected, the product derived from Aqua images has a higher success (78.41%) than Terra acquisitions (Table 5.5) for the whole study area, and a higher rate of non-fire events (Table 5.6). This difference should be related to the differences in saturation levels for the MODIS sensor, which are significantly lower in the Aqua satellite (the increase in temperature of saturation increases the detection of forest fires) that in Terra, which increases false alarms and improves true detections. The RRS is effective for detecting forest fires greater than 1 ha, showing a high percentage of outbreaks related to other causes, especially to agricultural burnings. The data obtained supplement official statistics and made it possible to check and correct the positions of the fires recorded in the GEOREF system.

**Table 5.5** Non – Forest fires detected by Aqua and Terra

| Region | Aqua | Terra | Total | % Aqua | % Terra |
|---|---|---|---|---|---|
| Valparaiso | 10 | 7 | 17 | 58.82 | 41.18 |
| Santiago | 6 | 5 | 11 | 54.55 | 45.45 |
| Libertador Bernardo O"Higgins | 48 | 11 | 59 | 81.36 | 18.64 |
| Maule | 50 | 19 | 69 | 72.46 | 27.54 |
| Total | 114 | 42 | 156 | 73.08 | 26.92 |

**Table 5.6** Fires detected by Aqua and Terra

| Region | Aqua | Terra | Total | % Aqua | % Terra |
|---|---|---|---|---|---|
| Valparaiso | 22 | 7 | 29 | 75.86 | 24.14 |
| Santiago | 13 | 4 | 17 | 76.47 | 23.53 |
| Libertador Bernardo O"Higgins | 19 | 4 | 23 | 82.61 | 17.39 |
| Maule | 15 | 4 | 19 | 78.95 | 21.05 |
| Total | 69 | 19 | 88 | 78.41 | 21.59 |

### *5.4.3 Quantification of Areas Burned by Product of Reflectivity of 32 Days MODIS*

This exercise tried to quantify the burnt areas (larger than 250 ha), using a non-standard MODIS product named "32 days reflectance MODIS", which is based on the standard 8-day composite product (MOD09A1). The 32-day reflectance includes bands 1 to 7 of the MODIS sensor at 500 m spatial resolution. This composite is generated by selecting for each pixel the 8-day composite with the second lowest reflectance in the series, with the intention of eliminating clouds and shades (Wan 1999; Barrientos 2006).

The results of the burnt surfaces are compared with the same measurements realized in Landsat-TM images and with the information determined for the respective forest fires by CONAF

The quantified fires correspond to the commune of Valparaiso, in the communes of Villa Alemana and Limache, the days November 19 and December 11, 2003, for which CONAF determined that 1.500 ha and 1.041 ha were burned.

#### 5.4.3.1 Data Processing

Color composites of mid infrared, near infrared and red (bands 7,2,1) for the MODIS image and 7,4,3 bands for the TM image were used. In this latter case, it was used the band 7 (2.08–2.35 μm) instead of band 5 (1.55–1.75 μm) due to the higher sensitivity of this band to char discrimination. The Landsat-TM image was taken on December 13, 2003 and the MODIS reflectance composite is within November and December, 2003.

For both images the corresponding corrections geometric were applied, using ground control points (GCP) based on a corrected image and vectors, with a third order polynomial and nearest neighbor resampling, not to alter significantly the original values. Windows around the burnt zones were extracted from the corrected images (Fig. 5.5).

#### 5.4.3.2 Image Classification

Both MODIS and TM images were classified using a supervised algorithm. Sampling zones within burnt areas were selected as training fields using seeding tech-

**Table 5.7** Quantification on compound MODIS and information TM

| Quantification Fires | Area affected Landsat TM | Terra MODIS |
|---|---|---|
| 19-11-2003 | 885.2 | 1.006 |
| 11-12-2003 | 1,151.5 | 1.236 |

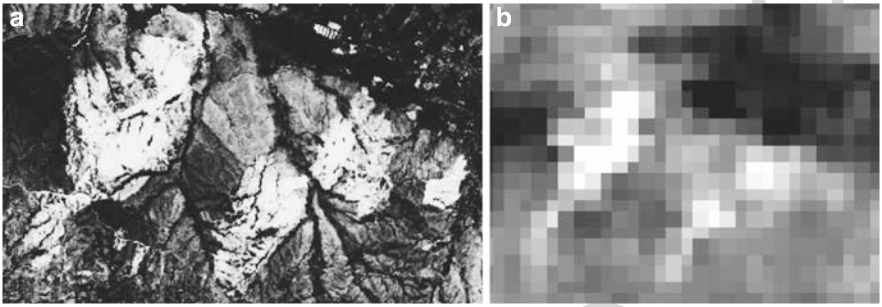

**Fig. 5.6** Results of burnt area discrimination: (**a**) Landsat-TM image, (**b**) MODIS image

niques. The maximum likelihood algorithm, with null class was selected. Surfaces corresponding to the areas burned in the data MODIS and Landsat are presented in Table 5.7 and Fig. 5.6.

On average, MODIS data showed an overestimation of about 100 ha, that corresponds to commission errors. A similar quantification, derived from the RSS gives a difference of 130 ha. The same methodology applied to 10 forest fires of the Central Zone of Chile with burnt areas greater than 62.5 ha, provided in 6 cases an average underestimation of 50.2 ha compared with the data, while in 4 fires it was shown an overestimation of 26 ha.

Another similar experience was performed to measure the burnt area in the National Park of “Torres del Paine”. In this case, the processing was based on the NDVI product of the RRS. The results provided an error of 15 ha, compare it with measurement using GPS (Castro 2005). The above, would allow to validate the use of data RRS (image composition B1,4,3, at 250 m resolution) to perform preliminary estimates of surfaces burned more than 62.5 ha.

## 5.5 Forest Fires Effects in the Vegetation of the Coastal Zone of Central Chile

Fire is a disturbance that has molded the structure and composition of the natural plant communities through the times (Whelan 1995), fact that is clearly reflected in the Mediterranean ecosystems, where communities have been developed and evolved as response to fires whose origins are from before the appearance of man

(Galtieri and Rodríguez 1974; Whelan 1995). As result of this, the species have adapted and survived, with capabilities to re-appear vegetatively from bud located in different organs, becoming necessary for the germination and establishment of many of them.

In the Mediterranean Central Zone of Chile, plants present particular characteristics that facilitate them high resilience and resistance after a forest fire, specially the case of sclerophyllus formations (Castro 2000). Nevertheless, the recurrence of fire in certain places degrade formations and replace species originating by exotic species.

The vegetation, in general, is highly susceptible to fires, especially by climate characteristics, with a marked and long summer season, warm and dry, favored for the coastal winds and the density and continuity of fuel, specially herbaceous annual stratum presents dry at the end of spring (Avila et al. 1988; Quintanilla and Castro 1998).

In the Mediterranean area of Chile, forest fires are a source of environmental degradation (Quintanilla 1996). The surface of native vegetation affected is cyclical and is always greater that the surface burned plantations (Castillo 2005). In the coastal zones, on the other hand, the vegetation formations are subject to multiple other factors of stress, along with fire, which impact negatively on the development and conservation of structures and floral compositions, as well as in the own existence of communities. Factors include: the pressure of the owners by change of land use, the extraction of firewood, included the underground parts of the different individuals, the extensive livestock, the clearing of vegetation opening of trails, flowers, seeds and individuals full purposes ornamental, soil compaction by trampling due to the transit of people (Otaria 2006).

### *5.5.1 Indicators of Condition Vegetation Post-Fire*

Indicators of post-fire condition of vegetation were developed for the Coastal Zone, based on a methodology of "patches". The study took place at the coastal plains presents at the sector of El Puquén. Sectors of vegetation that were affected by the fire with sectors that were unburned were compared, considering controlling biophysical factors such as topography, slope exposure and soil type. A stratified sampling with patches of multi specific trees and shrubs dominated by individuals of *Pouteria splendens* (Closed Patches), separated by more open sectors dominated by low shrubs and herbs (Opened Patches). The patch is a widely used concept in Landscape Ecology and it is defined as "homogeneous parts which differ from around", that is equivalent to a micro habitat or to parts of a tile. Distinctive patches of *Pouteria splendes* were selected. We identified four conditions or patches: Closed not burnt Patches (CNQ), Closed burnt Patches (CQ), Opened not burnt Patches (ANQ) and Opened burnt Patches (AQ).

For each patch 18 sampling units were arranged, totalling 72 sample units. The distance between the closed patches and the opened patches was between 15 to 30 m. preferably in the south-east direction. Inside every unit, 4 quadrants of $2 \times 1$ m were

extracted. where the vegetation was studied, taking information of presence and absence for all the vascular plants. The results obtained were allowed to determine the floristic composition and the following indicators:

### *5.5.2 Floristic Composition*

This is a basic data and represents the richness family and is suggestive of diversity taxonomic. In this case, were identified 126 species grouped in 44 families, of which 35 are present in the Closed not burnt patch, 35 in the burnt Enclosure, 38 families in the patches opened without burning and 42 in the patches Opened burned, being the most abundant. In all the types of patches the richest families are in descending order: Compositae, Gramíneae and Fabaceae.

Floral richness reflected the presence or absence of species in a vegetal community considering all the vascular species present in the area. The opened patches have a significantly more species (ANOVA, $F = 151$, g.l. $= 1$, $p << 0.05$) as the burnt patches, a significant interaction being detected between the factors fire and patches (ANOVA, $F = 36, 12$, g.l. $= 1$; $p << 0.05$).

### *5.5.3 Index of Jaccard's Similarity ($S_J$)*

This indicator is a measure of the similarity in species composition of two communities; this index is used to qualitative data presence/absence, and shows the relationship between the number of species found in common in two communities and the total number of species that are present in both. Does not consider the abundances, so that all the species have equal weight in the equation, regardless of their greater or lesser amount.

$$Sj = \frac{c}{a + b + c}$$

where: a = number of exclusive species of the treatment A; b = number of exclusive species of the treatment B; c = common species in the treatments A and B. The index varies between 0 and 1 and is equivalent to the percentage of shared species. In this case the highest value corresponded to the patches AQ and ANQ (0.70), whereas the floral similarity between the patches CNQ and CQ is only of (0.5), which implies that on the landscape having be burned, the increase of the floral similarity is statistically significant.

### *5.5.4 Life Forms and Fraction of Allochthonous*

To compare the physiognomy vegetal formations in each type of patch, species were classified according to their way of life in trees, shrubs, herbs perennial and

annual. Additionally, they were characterized according to its geographical origin (native/allochthonous) to use the proportion of allochthonous present, as an indicator of variations caused by the fire.

The result obtained, indicates that the percentage of shrubs is greater in the closed unburnt patches (CNQ) (24 %) than in the closed burnt patches (CQ) (16 %), like the perennials herbs with 40 and 32 % share respectively. But the only significant variance corresponds to the increase of annual herbs in patches CQ with regard to the CNQ (proportions test $Z = 1.92$; $p < 0.05$). The participation of the different forms of life in the patches open after the fire do not have significant variations.

To compare species composition, in terms of the origin, natives and allochthonous is observed that fraction of allochthonous is significantly greater in patches open in the closed (ANOVA, f = 18, 28, g.l. = 1; $p << 0.05$); on the other hand patches burned increase significantly the fraction of allochthonous (ANOVA, f = 35, 53; g.l. = 1; $p << 0.05$); a significant interaction being detected finally between fire and type of patch (ANOVA, F = 27, 36; g.l. = 1; $p << 0.05$).

Of the litoral vegetation that is affected by fires produce significant changes in vegetation, increase the richness of species and increasing the proportion of allochthonous species; effects that are more intensive patches closed, mainly because of the income of annual allochthonous by opening canopy.

To landscape, the fire also increases the similarity between floristic patches closed and open. The arboreal and shrub species typical are present, which translates later in the recovery of the landscape as succession and these again place returning the allochthonous (typically intolerant shade) to open spaces, to develop a process of resilience in the vegetal wealth.

In general, the Mediterranean territory of Chile, has had a long history of events of human disturbances, such as livestock, harvest wood and non – wood products, AQ5 long droughts (Montenegro et al. 1998). Nevertheless, it is possible to suggest that the vegetation of the littoral and of the Mediterranean zone in set, which is recognized by the biological diversity (CONAMA 2006), has the ability to recover due to the different adaptative strategies of their species. With everything, the forest fires, nevertheless, by the recurrence of these, is one of the most significant disturbances that can modify the physiognomy and structure of the vegetal formations, significantly reduce biodiversity indicated.

# Chapter 5

| Q. No. | Query |
|---|---|
| AQ1 | Au: "INFOR 2006" is not listed in the reference llist. Please provide. |
| AQ2 | Au: "INFOR 2003" is not listed in the reference list. Please provide. |
| AQ3 | Au: Please specify whether “Justice et al. 2002” is “2002a” or “2002b”. |
| AQ4 | Au: Please specify whether "Quintanilla, 1996" is 1996a" or "1996b". |
| AQ5 | Au: "Montenegro et al., 1998" is not listed in the reference list. Please provide. |

# Chapter 6
# Weather Factors and Fire Danger in the Mediterranean

**Andrea Camia and Giuseppe Amatulli**

**Abstract** We recall the main elements of fire weather in the Mediterranean environment and present the Canadian Fire Weather Index (FWI) System as the fire danger rating system currently most widely applied in the Mediterranean Europe. We also present the results of some calibration studies of the FWI System components carried out in the Mediterranean environment by various authors. Secondly, we look at the distribution of FWI System components values during the 2,816 major fires (i.e. fires with final size > 500 ha) recorded in Southern Europe in the last 28 years. Finally we present a regression model we have developed that predicts ($R^2 = 0.87$) monthly burned area in the European Mediterranean basin from monthly averages of the Initial Spread Index (ISI) and Drought Code (DC) components of FWI, valid for the months May to November.

## 6.1 Fire Weather in the Mediterranean Environment

Weather is a fundamental component of the fire environment. The prolonged drought and high temperatures of the summer period in the Mediterranean climate are the typical drivers that demarcate the temporal and spatial boundaries of the main fire season.

The dramatic 2003 and 2005 summers in South-western Europe (Portugal, Spain and Southern France) were above all triggered by an unprecedented heat wave and by extreme drought conditions respectively (Trigo et al. 2006; Viegas et al. 2006); similarly, the record severe conditions of 2007 in South-eastern Europe (Southern Italy and Greece) were driven by an explosive mix of strong winds and extremely high temperatures, following prolonged drought periods (European Commission 2008; Xanthopoulos 2008).

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Weather affects the moisture content of dead wildland fuels through various physical processes such as water vapour adsorption, condensation (dew formation), evaporation, and desorption, in addition to the direct contact with liquid water after rainfall (Viney 1991). Such processes are primarily driven by weather and several models of various complexities have been developed in the last decades that allow the estimate of dead fuel moisture content from meteorological readings (Camia et al. 2003). For the operational application of such models in the Mediterranean previous calibrations are often advisable (Lawson and Armitage 2008; Viegas et al. 2004).

Synoptic meteorological conditions associated with typical wind profiles (Brotak 1991) and atmospheric instability near the earth surface (Brotak and Reifsnyder 1977; Haines 1988) have also been identified as important weather parameters related to extreme fire conditions. In Europe mesoscale circulation patterns that develop during the summer have been described and recognized as important drivers of fire activity particularly in Spain (Millán et al. 1998) and in Portugal (Viegas et al. 2006).

The live fuel conditions of shrubs and grasses (i.e. moisture content but also related properties of fuel complexes changing with time such as the dead/live mixture or the degree of curing in grasses), are also quite important aspects of fire danger in the Mediterranean area. It is well known that the moisture content of live fuel is mostly linked to plants' phenology, although it is also affected by long-term soil water deficit at the roots level (Simard et al. 1989).

As a matter of fact, the live fuel moisture content of shrubs and herbs in the Mediterranean is influenced by the typical summer drought and the related soil water reserve (Castro et al. 2003) therefore it may change significantly from year to year. In Central Portugal the Drought Code of the Canadian Forest Fire Danger Rating System (Stocks et al. 1989) was fairly well related with the moisture content of live fine fuels of some shrub species during summer (Castro et al. 2003; Viegas et al. 2001), and similar results were found in Sardinia, Italy (Pellizzaro et al. 2007).

On the other hand foliar moisture content of conifer trees is reported to vary with species and season only (Scott and Reinhardt 2001); based on this assumption in the Canadian Forest Fire Behaviour Prediction System, foliar moisture content is not considered affected by weather but estimated from location, elevation and date only (Forestry Canada Fire Danger Group 1992).

## 6.2 The Application of the Canadian Fire Weather Index (FWI) System in the Mediterranean

### *6.2.1 Basis*

Fire danger is defined in (Merrill and Alexander 1987) as "a general term used to express an assessment of both fixed and variable factors of the fire environment that determine the ease of ignition, rate of spread, difficulty of control and fire

impact(s)". The fire danger rating systems most widely applied operationally are focused on the indirect assessment of dead fuel moisture content from the systematic recording of weather variables through time.

The fire danger rating method currently used in most of the European Mediterranean countries is the Canadian Fire Weather Index (FWI) system (Van Wagner 1987) of the Canadian Forest Fire Danger Rating System (CFFDRS) which is the national system of fire danger assessment in Canada (Stocks et al. 1989).

Although developed for the boreal forests of Canada, the FWI system has been show to have fairly good performances in the Mediterranean environment as compared to other fire danger indices (Viegas et al. 1996, 2000). Today a number of national fire services in Europe are currently using the FWI system to assess fire danger level in the country. Additionally, following the mentioned research results and after some years of testing, the FWI system has been adopted as a basis for fire danger assessment in the European Forest Fire Information System (EFFIS) (Camia et al. 2006), a system managed by the Joint Research Centre of the European Commission, providing daily large scale assessment and forecast of fire danger level throughout Europe[1] (Camia et al. 2007; European Commission 2008).

The CFFDRS has been developed for assessing fire danger potential and predicting fire behaviour in Canadian forests. It is composed by two major subsystems: the Canadian Forest Fire Weather Index (FWI) System (Van Wagner 1987) and the Canadian Forest Fire Behaviour Prediction (FBP) System (Forestry Canada Fire Danger Group 1992).

The FWI System has six components rating fuel moisture content and potential fire behaviour in a common fuel type of Canada (i.e., mature pine stand) and in no slope conditions. Calculations are based on daily noon measurements of air temperature, relative humidity, wind speed and 24-h cumulative precipitation. The first three components are numerical rating of the moisture content of forest floor layers with different drying rates and at various depths. The Fine Fuel Moisture Code (FFMC) rates the moisture of litter and other dead fine fuels at the top of the surface fuel layer; the Duff Moisture Code (DMC) rates the moisture of the loosely compacted organic layer of moderate depth; the Drought Code (DC) represents the moisture content of the deep layer of compact organic matter. The three moisture codes carry different useful information being indicators of ease of ignition and flammability of fine fuels (FFMC), fuel consumption in medium-size woody material and moderate duff layers (DMC), fuel consumption in large logs and amount of smouldering in deep duff layers (DC) (Alexander 2008).

The last three codes are fire behaviour indices rating the expected rate of fire spread (Initial Spread Index – ISI) from the combination of FFMC and wind speed, the fuel available for combustion (Build Up Index – BUI) from the combination of DMC and DC, and the fire line intensity (FWI) which is the final index that combines ISI and BUI and rates the energy output rate per unit length of the fire front, according to Byram's formulation (Byram 1959).

[1] http://effis.jrc.ec.europa.eu

As a matter of fact each individual component of the FWI system is a fire danger index, revealing different aspects of fire danger which are finally difficult to synthesize with one single number (Alexander 2008).

Another important aspect is that the FWI output only depends on weather observations and does not consider differences in fuel types or topography, providing a uniform, relative way of rating fire danger through fuel moisture and fire behaviour potential (Van Wagner 1987).

The FBP subsystem complements FWI, extending the fire behaviour prediction to 16 different fuel types and introducing the slope effect, therefore allowing quantitative estimates of certain fire behaviour characteristics for each specific fuel type and topographic situation, based on the components of the FWI System.

It is worth noting that the mentioned models have been originally developed for the assessment of fire potential in a given site with input data coming from a point source, therefore the CFFDRS is non-spatial system; nevertheless it provides the foundation for the geospatial applications and fire management information systems that produce fire danger related maps allowing the assessment and mapping of the spatial distribution of fire potential (Lee et al. 2002). The EFFIS system from March to October produces and publishes daily on the web maps of fire danger in Europe based on the FWI System (Camia et al. 2006).

### *6.2.2 Calibration Studies of the FWI System in the Mediterranean*

Since the first applications of the FWI System in the Mediterranean environment, several studies have been done to calibrate the indices and assess their performances.

In Southern Europe the FFMC has been found to correlate fairly well with leaf litter moisture content (Aguado et al. 2007; Viegas et al. 2004) and a calibration curve has been developed for pine and eucalyptus litters in Portugal (Viegas et al. 2004). The DMC fits less the moisture content of duff (Dimitrakopoulos and Bemmerzouk 1998; Fernandes 2005) although relationships with decomposing leaves in conifer forest floors have been shown (Fernandes 2005). The DC, the moisture code with the longer drying rate, is a useful indicator of seasonal drought effects on forest fuels (Alexander 2008), for the application in the Mediterranean environment it is likely the most questionable of the three moisture codes, as in the large majority of cases the soil deep organic layer is absent. Nonetheless, as previously mentioned, DC has been found to be correlated with live fuel moisture content of Mediterranean shrubs (Castro et al. 2003; Ceccato et al. 2003; Pellizzaro et al. 2007; Viegas et al. 2001, 2004). In central Portugal DC showed some potential to assess the percentage of dead material in grasslands at the end of the spring (Viegas et al. 2002) and its seasonal average was reasonably fitting the total burned area in the region (Viegas et al. 2004).

For the fire behaviour indices of the FWI System, a good relationship has been verified between the rate of fire spread and ISI for a wide range of conditions in pine forests of Portugal (Fernandes 2005; Palheiro et al. 2006). In shrub fuel complexes

the fitting was satisfactory in some cases (Viegas et al. 2004), and more controversial in others, presumably due to the high variability of shrub heights in the experimental dataset (Fernandes 2005).

Fewer examples are available on the assessment of BUI effect on fuel consumption in Mediterranean fuel types. Some experimental results are available for forest floors in maritime pine plantations (Palheiro et al. 2006); the fitting found by the authors is poor, but the trend of changing fuel consumption with increasing dryness is reasonably described.

Still in maritime pine forest a reasonable fit of the observed fire intensity and FWI was found by (Fernandes 2005), and results were significantly improved when modelling the fire intensity directly from BUI and ISI. On the other hand for shrub fuels the goodness of fit was not enough to develop quantitative relations.

These results encourage the use of FWI as an indicator of fire intensity (Alexander and De Groot 1988) and therefore ultimately the application of Byram's (Byram 1959) fireline intensity concept to determine the fire danger level, focused on providing an estimate of the degree of containment difficulty should an ignition occur (Alexander 2008). This approach as developed by Alexander (see e.g. Alexander 2008; Alexander and De Groot 1988) is especially useful when applied to the calibration of FWI for the definition of fire danger classes, no doubt being the most focused and robust alternative.

Nonetheless it is worth noting that, with few exceptions (Fernandes 2005; Palheiro et al. 2006), the research work carried out until now on the calibration of the FWI index in the Mediterranean environment has been in most cases based on a different approach, i.e. on analyzing the distribution of days in each fire danger class or on predicting the expected fire activity in a given area and day based on statistical fitting of historical data series.

## 6.3 Weather Extremes and Major Fires in the Mediterranean

In this chapter we intend to look into the extreme branch of the fire danger spectrum, considering the FWI System components values during the major events occurred during the last decades in the Mediterranean Europe.

The fire database of EFFIS stores the records of historical fire events of the European countries. We have extracted from the database the 2,816 fire events reported with a final size exceeding 500 ha and occurred from 1980 to 2006 in the five most affected European Mediterranean countries (Portugal, Spain, France, Italy and Greece). Most of them were in the Iberian Peninsula and markedly concentrated from June to September (Table 6.1).

The largest fire recorded burned 25,430 ha in Spain on the 4th until 12th of July 1994. In Table 6.2 the number of major fires by final size and main fuel type affected is given. Fuel types considered are forest, shrublands and grasslands, as currently there is no additional information on fuel beds in the historical database; in Table 6.2 and in the rest of this chapter, fires are characterized by a unique fuel type

**Table 6.1** Number of major fires (>500 ha) in Southern Europe (1980–2006)

| *Month* | *Spain* | *France* | *Greece* | *Italy* | *Portugal* | **Total** |
|---|---|---|---|---|---|---|
| Jan | 2 | 2 | – | 14 | – | 18 |
| Feb | 17 | 2 | 1 | 27 | – | 47 |
| Mar | 22 | 2 | 3 | 31 | 10 | 68 |
| Apr | 22 | 5 | 2 | 6 | 4 | 39 |
| May | 8 | 1 | – | 2 | 2 | 13 |
| Jun | 42 | 7 | 18 | 14 | 42 | 123 |
| Jul | 259 | 24 | 130 | 95 | 274 | 782 |
| Aug | 431 | 30 | 117 | 89 | 542 | 1,209 |
| Sep | 181 | 4 | 52 | 15 | 159 | 411 |
| Oct | 30 | 3 | 11 | 3 | 30 | 77 |
| Nov | 6 | – | 1 | – | – | 7 |
| Dec | 17 | 1 | 1 | 2 | 1 | 22 |
| **Total** | 1,037 | 81 | 336 | 298 | 1,064 | 2,816 |

**Table 6.2** Number of major fires in Southern Europe (1980–2006) by fire size class and main fuel type affected

| *Fire size* | *Forest* | *Grassland* | *Shrubland* | *Mix* | **Total** |
|---|---|---|---|---|---|
| 500–1,000 ha | 321 | 220 | 269 | 843 | 1,653 |
| 1,000–2,000 ha | 147 | 96 | 84 | 370 | 697 |
| 2,000–5,000 ha | 92 | 19 | 27 | 223 | 361 |
| 5,000–10,000 ha | 22 | 6 | 3 | 42 | 73 |
| >10,000 ha | 15 | – | – | 17 | 32 |
| **Total** | 597 | 341 | 383 | 1,495 | 2,816 |

when it represented at least 80% of the burned area, otherwise they are qualified as mixed.

We computed the FWI components during the days of fire activity using ERA-40 re-analysis of meteorological observations by the European Centre for Medium-Range Weather Forecasts (ECMWF) (Uppala et al. 2006). As most of these large fires last for more than 1 day (about 90% of them ended within 7 days), the day with maximum FWI value was selected for each fire in order to characterize the peak fire danger conditions. Boxplots of the FWI System components in those days are given in Fig. 6.1, thus providing indication of the range of values than can be reached in extreme fire danger conditions in the Mediterranean.

The moisture codes, and in particular DMC and DC (and as a consequence BUI), in most of the cases have remarkably high values. Main differences between fuel types are evident in the ISI, which in turn makes the differences in final FWI values. We tested such differences by comparing the means with Tukey's HSD (Honestly AQ2 Significant Difference) test (Tukey 1953) for multiple post-hoc pairwise comparisons in the analysis of variance. The difference between all the fuel types was confirmed to be highly significant ($p<0.01$) for ISI and FWI, highly significant for DC, DMC and BUI except between grassland and shrubland (not significant), not

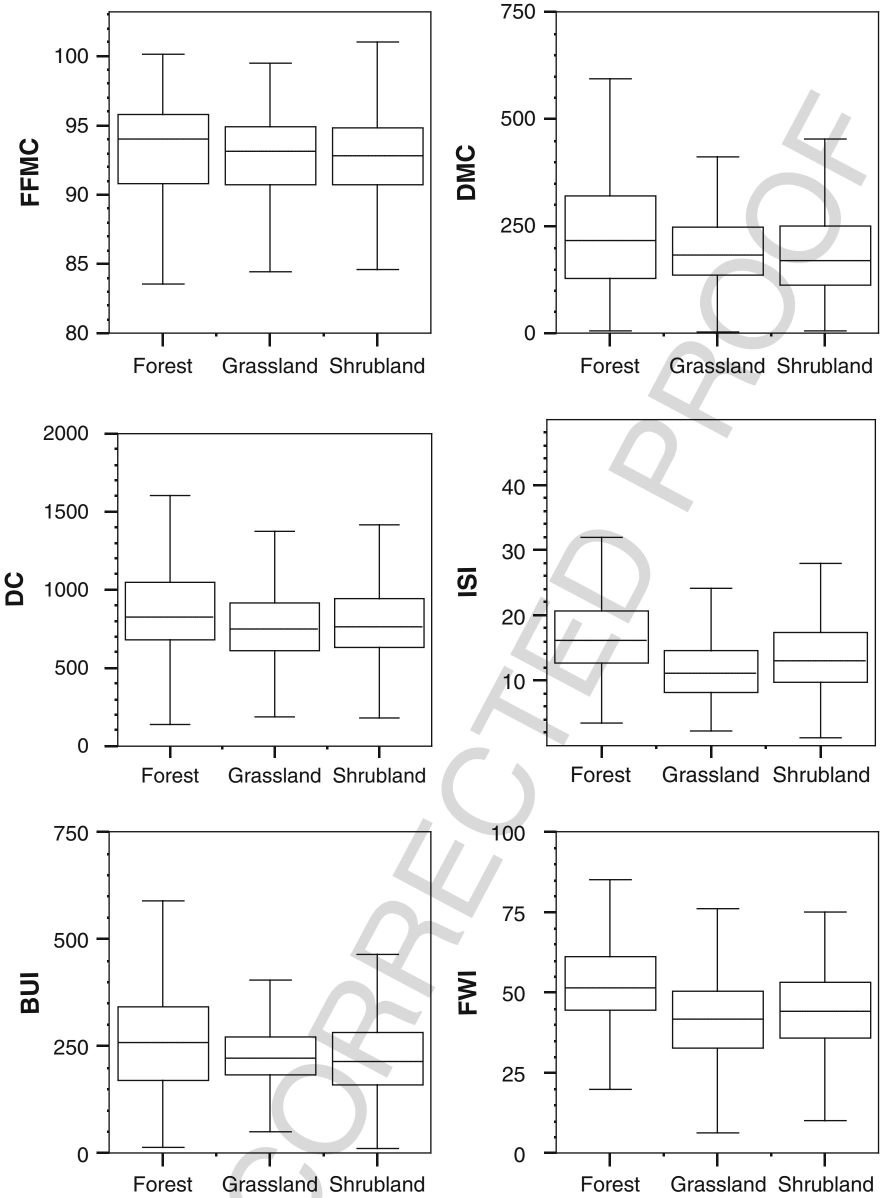


**Fig. 6.1** Boxplots of FWI system components in the peak fire danger days of 2,816 major fires (outliers and extreme values not shown)

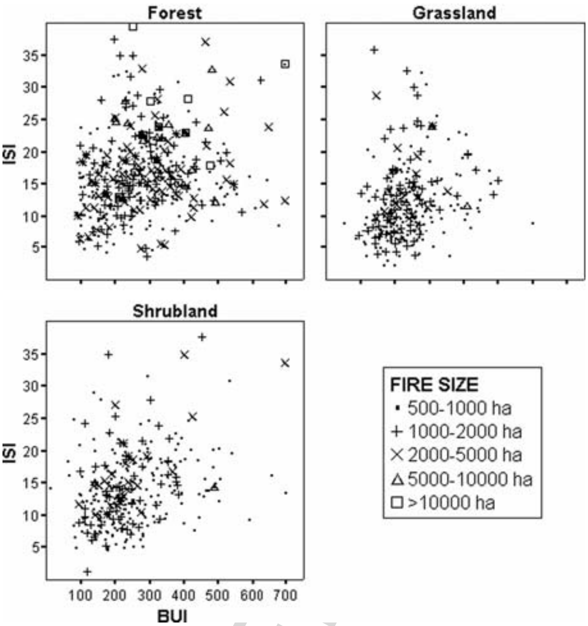


**Fig. 6.2** BUI and ISI components in the peak fire danger days of major fires (>500 ha) grouped by main fuel types, during the summer fire seasons 1980–2006

significant in all FFMC comparison. The variability found between fuel types is of course due to the intrinsic nature of the indices; it simply confirms the importance of selectively calibrating FWI components depending on the dominant fuel type of the application area.

The scatterplots in Fig. 6.2 show the joint ISI and BUI distribution only for large fires occurred during the summer season. As expected, in grasslands and shrublands ISI variability has a predominant role in relation to the final fire size as compared to BUI, while in forest lands this is less evident.

In Figs. 6.3 and 6.4 the final burned areas against ISI and BUI in spring and summer fires are given with a LLR (local liner regression) smoother curve to identify the main trends. The relationships are quite loose in fact as the indices are not meant to be directly related to the final burned area; nevertheless the observation of the trends is instructive. The extreme values reached by BUI somehow saturate, especially in grasslands and shrublands, so that further increase do not have a practical effect, while a small effect is still detectable in forests for the lower part of the BUI range.

The findings from fire behaviour experiments and direct observation done in Portugal clearly support this evidence. Following the analysis of experimental data (Palheiro et al. 2006) consider the effects of BUI on the rate of fire spread in maritime pine stands constant for values higher than 150. On the other hand, for shrublands, despite the availability of quite extended datasets, practical no relationship has been found (Fernandes 2005).

The ISI (Fig. 6.3) has a clearer relationship with the final fire size in all fuel types and in both seasons, with a more obvious trend in the forest.

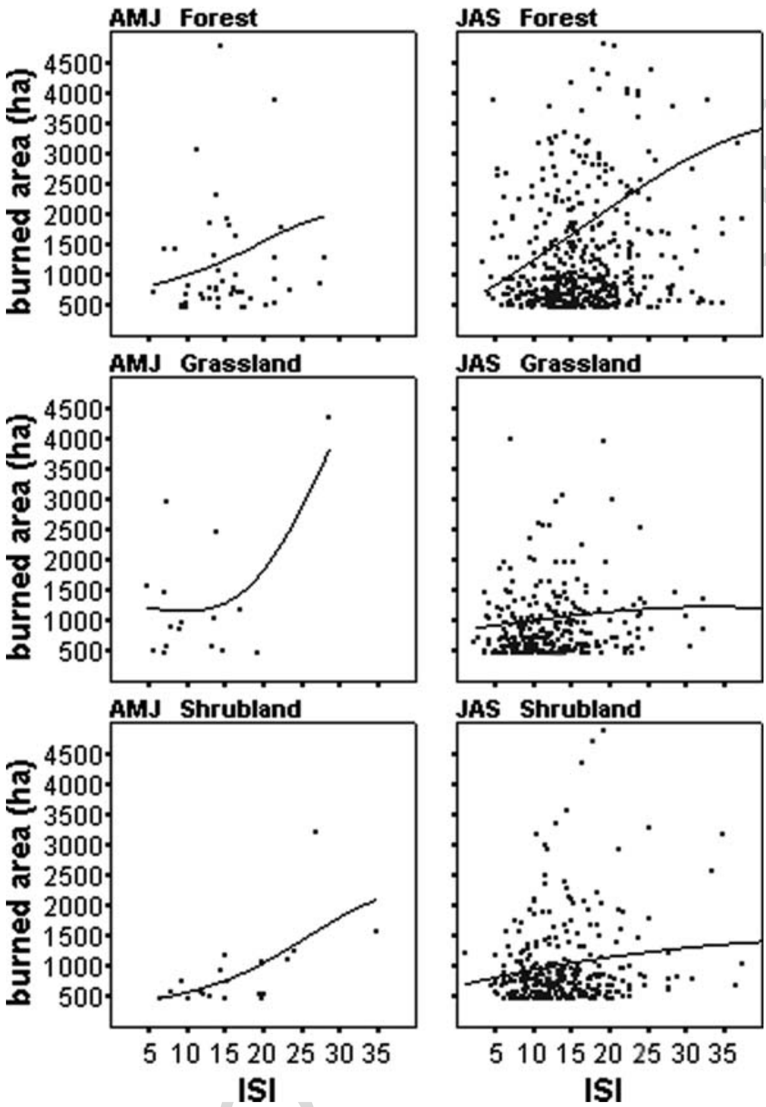


Fig. 6.3 Burned area of large fires (final size 500–5,000 ha) against ISI. Fires grouped by fuel type and season (AMJ spring, JAS summer). Lines are local linear regression (LLR) curves

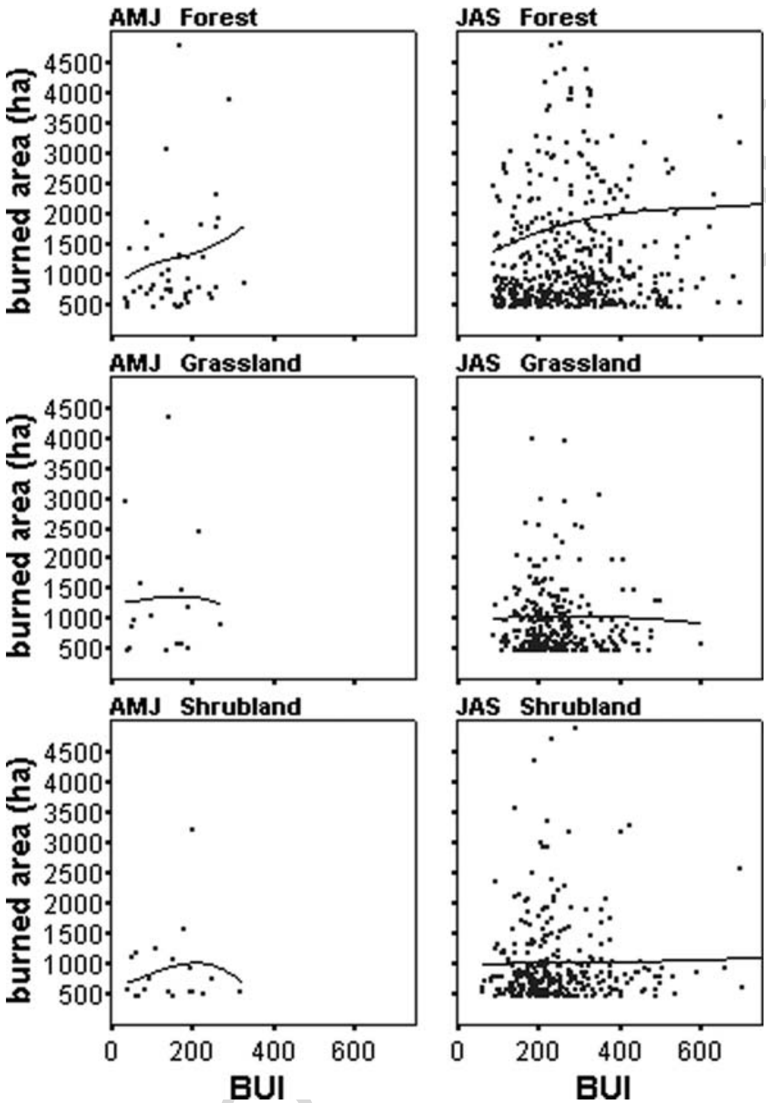


**Fig. 6.4** Burned area of large fires (final size 500–5,000 ha) against BUI. Fires grouped by fuel type and season (AMJ spring, JAS summer). Lines are local linear regression (LLR) curves

## 6.4 Seasonal Fire Activities and Average Weather

In addition to the daily assessment of fire danger, monthly or seasonal assessments are useful to compare different seasons or areas (Harvey et al. 1986), or analyze past trends (Camia et al. 2008). Today monthly ratings are becoming of additional practical interest with the increased availability and reliability of weather forecast

at seasonal timescale e.g. (Roads et al. 2006). The seasonal characterization of fire weather is also relevant in the context of climate change projections and analysis of the expected impact on fire danger (Flannigan et al. 2005).

A simple method to characterize the danger level in a given season based on the Canadian FWI System is to use a transformation of the daily FWI referred to as daily severity rating (Van Wagner 1987) and average it to obtain seasonal severity ratings (or monthly when averaged over a month (Stocks et al. 1998)).

We have tested the relationship of the monthly severity rating and of all the monthly averages of the other FWI System components against the monthly burned area over the European Mediterranean basin (Portugal, Spain, Southern France, Italy and Greece).

Data were taken from the EU Fire Database of EFFIS (years 1985–2004) and the corresponding FWI daily series was computed from the ERA-40 dataset (Uppala et al. 2006).

Separate multiple regression analysis were made for the summer-autumn (May to November) and winter-spring (December to April) periods.

In summer-autumn the best fit (adjusted $R^2 = 0.87$, $p < 0.001$) was found with the following equation:

$$BA = \exp(0.6422\ ISI_{avg} + 0.0035\ DC_{avg} + 4.8577)$$

In winter-spring the best fit (adjusted $R^2 = 0.68$, $p < 0.001$) was:

$$BA = \exp(0.1444\ FFMC_{avg} + 0.0018\ DC_{avg} - 1.8174)$$

where BA is the total burned area in the five countries of the European Mediterranean basin and the independent variables are the monthly averages of the corresponding FWI components, averaged over the same area. Table 6.3 summarizes some key statistics of the regression equations found, and in Fig. 6.5 we present the scatterplot for the summer-autumn period with the interpolating surface of the model. Interestingly enough the variables, selected with a standard stepwise regression procedure, are balanced in both models with spread and drought components.

**Table 6.3** Model coefficient estimates (B), standard errors (s.e) and significance (Sig.) of the regression equations that estimate the monthly burned area in the European Mediterranean basin

| Model | Variable | B | s.e. | Sig. |
|---|---|---|---|---|
| Summer-autumn | (Intercept) | 4.8577 | 0.1741 | 0.000 |
| (n=140; $R^2$=0.87) | $ISI_{avg}$ | 0.6422 | 0.0293 | 0.000 |
| | $DC_{avg}$ | 0.0036 | 0.0003 | 0.000 |
| Winter-spring | (Intercept) | –0.4751 | 1.1253 | – |
| (n=100; $R^2$=0.68) | $ISI_{avg}$ | 0.2544 | 0.1643 | – |
| | $FFMC_{avg}$ | 0.1149 | 0.0217 | 0.000 |
| | $DC_{avg}$ | 0.0023 | 0.0008 | 0.004 |

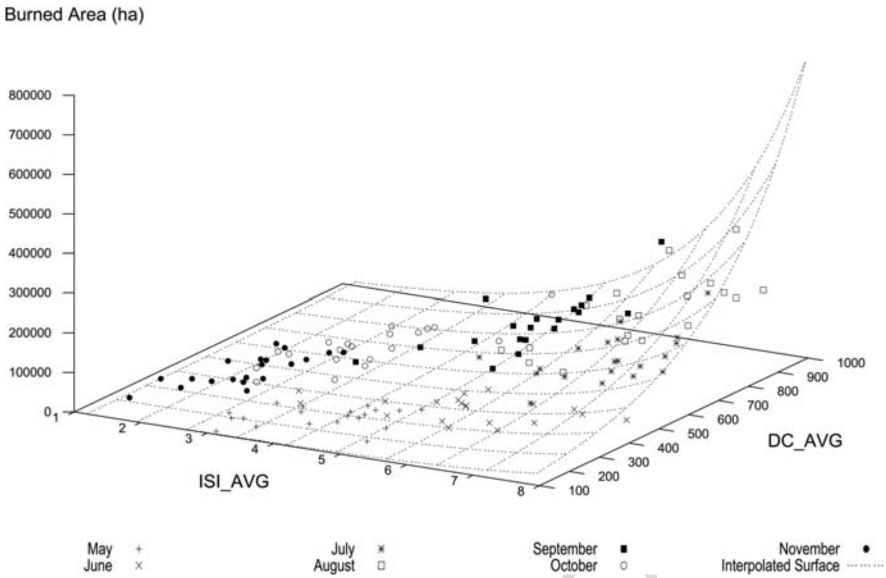


**Fig. 6.5** Monthly burned area against ISI and DC monthly averages in the European Mediterranean basin in months May to November 1985–2004, with interpolating surface

The summer-autumn model is by far the more interesting one, covering the entire main fire season of the Mediterranean area.

# Chapter 6

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# Chapter 7
# Estimation of Fuel Conditions for Fire Danger Assessment

**Emilio Chuvieco, Jan Wagtendok, David Riaño, Marta Yebra,**
AQ1 **and Susan L. Ustin**

**Abstract** A review of physical and chemical properties of fuels relevant for fire ignition and propagation is presented, along with different methods to estimate those properties, with special emphasis on satellite imagery. The discussion is more extended on estimating fuel moisture trends and fuel geometrical properties.

## 7.1 Fuel Properties Relevant to Fire Management

Fire occurs when fuels are heated within an oxygen rich atmosphere. The ignition and propagation conditions of any fire are, therefore, directly associated with fuel conditions, mainly bulk density, moisture content, and horizontal and vertical continuity.

In wildland fires, the main fuel available for burning is vegetation, which refers either to live plants (grass, shrubs, trees) or dead materials, mostly lying on the surface (leaves, twigs, organic soil). Estimating chemical and physical conditions of vegetation is, therefore, critical for assessing fire risk.

The main chemical variables affecting fuel interactions with fire are water content and oil contents. Water content, commonly called fuel moisture content (FMC), is directly related to fire ignition and fire propagation potential, because the proportion of water has a direct effect on ignition delay and fire rate of spread (Nelson 2001; Viegas et al. 1992). For this reason, the FMC is a common component of fire danger assessments (Blackmarr and Flanner 1968; Fosberg and Schroeder 1971; Paltridge and Barber 1988; Pompe and Vines 1966; Trowbridge and Feller 1988), FMC is also critical for planning prescribed burns (Baeza et al. 2002), and it has been shown related to burning efficiency, which is a critical component for estimating gas emissions from fires (Chuvieco et al. 2004a). In addition to cellulose, chemicals such as volatile oils and resins present in wood contribute to its heat content. However, the concentration of volatile oils in wood is so low that they affect

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plant flammability more through lowering the temperature needed for ignition of leaves than by increasing leaf combustibility (King and Vines 1969; Zylstra 2006). Minerals have the effect of lowering the heat content (Philpot 1970).

Numerous fuel characteristics are relevant for fire behavior modeling of crown fires and surface fires. Crown fuels are those that burn when a fire leaps into the canopies of trees. Properties of crown fuels that determine the rate and intensity of crown fires include canopy closure, canopy height, crown base height, and crown bulk density. Canopy closure is measured as percent cover, and affects fire behavior by shading surface fuels and thereby increasing fuel moisture, as well as by modifying winds that flow above the canopy (Albini and Baughman 1979). The higher the canopy the greater the reduction of wind speeds at the fire level and greater the distance to which embers can be lofted. Crown base height is the vertical distance from the ground surface to the base of the live crowns (Finney 1998), and determines the threshold for transition from a surface fire to a crown fire. Crown bulk density is the amount of foliar biomass per unit of volume of the forest canopy, and affects the threshold for spreading of fire from tree to tree.

Surface fuels typically include dead material on the ground as well as live and dead fuels in the herbaceous and shrub layers. Litter and small woody fuels are those fuels that lie on the ground and contribute to the passing front of the fire. Not included are large woody fuels and deep duff fuels that can burn and smolder for long periods after the fire has passed. Physical properties of surface fuels include size class and surface area to volume ratio, specific gravity, load by size class, and fuel bed depth. The horizontal and vertical arrangement of the fuel is also important for determining fire spread. The size class of fuel particles plays a critical role in fire behavior. The smaller the size of a fuel particle, the larger is the ratio between the surface and the volume, and therefore more surface area is available for heating and combustion. The weight per unit of volume of a fuel particle is called the particle density. The more dense the fuel particle, the higher the load and the greater the heat content. The amount of fuel that is potentially available for combustion is called the fuel load. The more fuel available, the greater amount of heat available for driving fire intensity and rate of spread. However, when fuel loads are very high, rate of spread may actually decrease, because more heat is required to raise it to ignition temperature.

Fuel properties are relevant for fire planning purposes, but they are difficult to estimate and map. In the following paragraphs we will review different approaches to retrieve these properties, with special emphasis on satellite remote sensing methods, which provide an up to date, spatially comprehensive monitoring of vegetation conditions. We will split the analysis in the two main groups of factors: chemical composition, with particular attention to FMC, and physical composition.

## 7.2 Estimation of Fuel Moisture Content

Different indices have been proposed to estimate vegetation water content. In remote sensing studies, the most common is the Equivalent Water Thickness (EWT),

measured as the ratio of leaf water content to leaf area because it provides a close approximation to the water absorption intensity (Ceccato et al. 2001). However, in the forest fire literature, a much more common variable is the proportion of water to total plant mass:

$$\mathrm{FMC} = \left(\frac{W_w - W_d}{W_d}\right) \times 100 \tag{1}$$

where $W_w$ is the wet weight of a given sample and $W_d$ is the dry weight of the same sample, usually after oven drying at 60°C–100°C for 24–48 h (Viegas et al. 1992). FMC and EWT can be related using the dry matter content (DM: ratio of leaf dry mass to leaf area) (Danson and Bowyer 2004; Yebra et al. 2008b).

### *7.2.1 Methods to Estimate FMC*

The most direct measurement of FMC is collecting fresh field samples, drying them until all moisture is evaporated, and computing the water content by weight difference between fresh and dry samples (Lawson and Hawkes 1989). Samples are collected periodically between 12:00 at 16:00, to consider drier, therefore riskier fire conditions. These measures are taken periodically. For dead and fine sized fuels, sampling is performed daily and even several times a day since FMC will vary with atmospheric humidity. While for live fuels, once weekly should be enough, because water is regulated more persistently than in dead materials (Viegas et al. 2001).

The spatial density of sampling sites should account for the variability of the target area. Transects or multiphase sampling techniques are recommended to account for local variations. When monitoring multitemporal trends within a selected species, it is preferable to sample the same plant. Most authors recommend sampling just leaves, while others include branches as well. Within leaves, the sampling can be focused on just the terminal shoots or it can include old leaves as well. This decision is particularly critical in semi-deciduous species, which will have a strong contrast of moisture conditions between the spring and summer (Nuñez-Olivera et al. 1996).

Field sampling of FMC is simple to perform and relatively accurate, but it is costly and difficult to generalize, especially when the fire manager wants to obtain regional estimations. For this reason, field data is commonly used for calibration or validation purposes (Chuvieco et al. 2004b), but not for operational management. Much more common is the estimation of FMC based on meteorological indices, because weather data are easily accessible and include other variables that are critical for fire risk assessment. In fact, most fire danger indices currently operational include some estimate of moisture conditions. The vast majority focus on dead materials (Camia et al. 2003), although a few also include meteorological variables to estimate FMC of live species (Burgan et al. 1998; Sebastián-López et al. 2002; Viegas et al. 2001). Although meteorological indices are widely used, the estimation of FMC conditions presents two important problems. First, meteorological data are only available at sparse locations, where the weather stations are located.

Interpolation algorithms are used to obtain a spatially comprehensive view of the proposed indices, which frequently have large errors due to inadequate sampling. The second problem affects the indirect character of the FMC estimation. Meteorological indices assume a constant relation between atmospheric conditions and FMC variations, but in the case of live fuels, physiological mechanisms and soil conditions have a critical role in the actual FMC. In fact, different species in the same area can have very different FMC.

### 7.2.2 Estimation of FMC from Satellite Data

Because of limitations of field methods and meteorological indices, satellite estimation of FMC conditions provides a sound alternative, particularly for live fuels, because it is spatially comprehensive and can provide frequent temporal observations of actual plant conditions. Obviously, the challenge in this case is to prove that the impact of FMC variation on the detected signal (reflectance, temperature) is strong enough to be discriminated from other factors affecting spectral variation.

Several studies have been published in the last decades to test this hypothesis. They can be grouped in two categories: those based on empirical fittings and those based on simulation models. The former rely on statistical methods, while the latter on the physical bases (Fig. 7.1). A more detailed discussion of both types of models follows in the next section. Before reviewing them, we will comment briefly the spectral basis for detecting water content in remotely sensed images

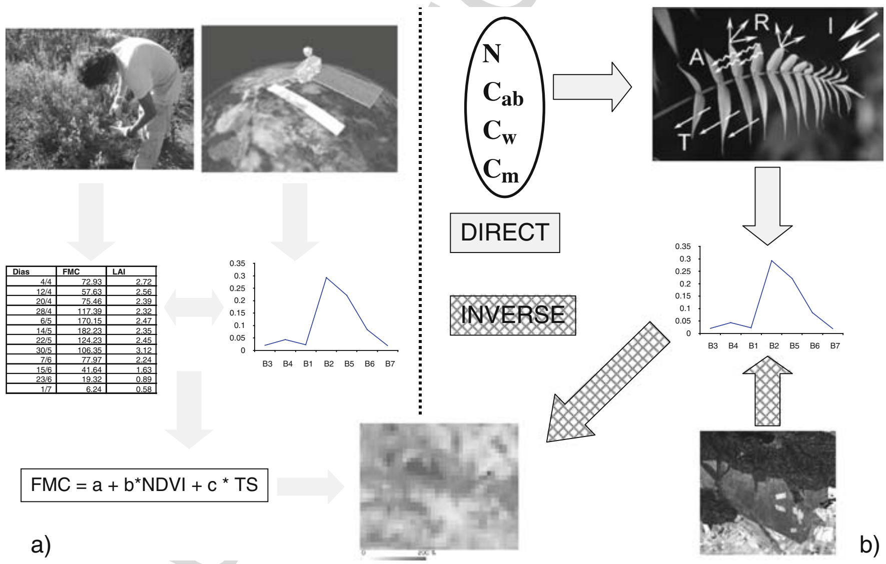


Fig. 7.1 Plant water content can be retrieved from using empirical (a) and simulation (b) models

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#### 7.2.2.1 Spectral Response of Water Content

Both empirical and simulation approaches focus on those spectral bands that are the most sensitive to water content variation or those where separation from other variations affecting water content is more evident. Many studies have identified the short-wave infrared (1.2–2.5 μm) as the most sensitive band to water absorption in the solar spectrum (Aldakheel and Danson 1997; Baret and Fourty 1997; Carter 1991; Danson et al. 1992; De Santis et al. 2006; Gillon et al. 2004; Hunt 1991; Sims and Gamon 2003). Therefore, these wavelengths are the best for direct estimation of water content.

However, other factors also affect reflectance in those spectral bands, and therefore a multispectral approach, based on combining spectral reflectance in two contrasting bands has been proposed (Ceccato et al. 2002a, 2001; Datt 1999; Hunt and Rock 1989; Hunt et al. 1987; Westman and Price 1988). Most of those studies are based on EWT and not FMC, which is even more difficult to estimate, since variation in DM needs to be accounted for (Danson and Bowyer 2004).

An alternative to the SWIR bands is using an indirect estimation of water content variation, based on the impacts of water shortage on chlorophyll content and leaf area index (LAI). This is the basis for using the normalized difference vegetation index (NDVI) for monitoring water stress and fire risk conditions (Hardy and Burgan 1999; Illera et al. 1996; Leblon et al. 2001). This approach may work in some vegetation functional types (mainly for herbaceous and deciduous plants) where water changes affect chlorophyll or LAI variations, but not in perennial species that have different strategies for reducing water stress (especially evergreen trees and shrubs). For this reason, correlations between FMC and NDVI trends have been found inconsistent in evergreen trees and shrubs (Ceccato et al. 2001; Chuvieco et al. 2004a, 2002).

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The estimation of plant water content has also been attempted using thermal imagers. If the plant is well drained, rises in air temperature will also increase evapotranspiration and modify the energy balance of the species. This increase in latent heat concurrently reduces sensible heat, and consequently decreases leaf temperature. However, when the plant dries, transpiration is reduced and consequently, so does latent heat, whereas sensible heat increases simultaneously and canopy temperature rises (Kozlowski et al. 1991). As a result, the difference between air and surface temperatures is clearly related to plant water content and to estimated water stress.

#### 7.2.2.2 Empirical Approaches

The empirical methods are commonly based on statistical fitting between field measured FMC and reflectance data. They have a known accuracy and are simple to compute, although they require simultaneous field data collection and image acquisition for calibration and validation. In addition to this problem, empirical relationships are sensor and site dependent, and therefore difficult to extrapolate to

regional or global scale studies due to differences in leaf and canopy characteristics (Riaño et al. 2005) or sensor calibration and observation conditions.

Most empirical estimations of FMC have been based on coarse resolution sensors, because they provide the adequate temporal resolution for operational estimation of this very dynamic variable. Several studies found good agreements between NDVI temporal series derived from NOAA/AVHRR images and FMC of grasslands (Burgan et al. 1996; Chladil and Nunez 1995; Paltridge and Barber 1988). Other authors suggested to use NDVI and surface temperature (ST) images, to improve the estimation of shrub covered areas, where the relations between chlorophyll or LAI and water are much less evident (Alonso et al. 1996; Chuvieco et al. 2004b). Similar results to AVHRR were found for higher resolution sensors, such as Landsat-TM/ETM+ (Chuvieco et al. 2002; Hardy and Burgan 1999).

Other researchers have used empirical methods to estimate FMC from MODIS or VEGETATION images, which have bands in the SWIR (Chuvieco et al. 2004a; Dennison et al. 2005; Roberts et al. 2006b). However, the results for shrubs are not as good as expected from the SWIR bands, and trends are not conclusive. Actually, with Mediterranean ecosystem shrub species, a visible and near infrared (NIR) index, named VARI (Gitelson et al. 2002), has produced even better results than indices based on the NIR and SWIR bands (Roberts et al. 2006b; Stow et al. 2005; Yebra et al. 2008b).

The most recent proposal for empirical estimation of FMC is based on NDVI, surface temperature (ST), and a set of functions for the day of the year (Garcia et al. 2008). The empirical model is selected based on regional drought stress, as measured by the Cumulative Water Balance Index: (Dennison et al. 2003), a climatic index that takes into account the difference between precipitation and reference evapotranspiration over a specified time period.

#### 7.2.2.3 Simulation Approaches

Estimation of water content from simulation approaches has frequently been based on inversion of Radiative Transfer Models (RTM). Because these models are based on physical relationships that are independent of sensor or site conditions, they should be more universal than empirical fittings. In this sense, Yebra et al. (2008b) estimated LFMC from Terra-MODIS data by comparing the performance of empirical and simulation approaches. They observed that both models produced good results, although RTM provided more robust estimations, and consequently had a greater generalization power. This hypothesis was tested in Yebra et al. (2008a) when comparing the performance of empirical and simulation models in grasslands of central Spain and Australia. In both sites, similarly accurate results were obtained when using RTM, but empirical models performed poorly in the Australian sites that had different structure and composition from the Spanish calibration site.

In spite of the high interest of RTM, these models present several problems for accurately estimating FMC:

1. The selection and parameterization of these models is far more complex than empirical models, because they are based on assumptions that may not accurately

resemble those found in nature, especially when complex canopies are involved (Liang 2004). For example, RTM do not take into account ecophysiological relations between their input parameters (Yebra and Chuvieco 2008).

2. The inversion of RTM presents uncertainties because very similar reflectances can be derived from a different set of input parameters, a well known ill-posed inverse problem (Garabedian 1964).

3. Related to the previous problem, if the inversion starts from unrealistic situations, for example, unrealistic parameter combinations, they might provide poor estimations because the probability of an ill-posed inversion increases considerably (Yebra and Chuvieco 2008).

4. The solution is inversion-method dependent.

Consequently a prior knowledge of plant biophysical parameters should be used to constrain the input parameters of the RTM to model conditions as closely as possible to the actual canopy state (Combal et al. 2002). Some authors have chosen to include data derived from satellite imagery as input parameters (Zarco-Tejada et al. 2003). Others have relied upon experimental data in controlled conditions (Riaño et al. 2005). Recently, Yebra et al. (2008b) and Yebra and Chuvieco (2008) proposed using ecological rules to avoid simulating unrealistic spectra, where the parameters present values never met simultaneously on the field (Fig. 7.2). The authors first analyzed how the different parameters used in the RTM co-evolve in shrublands

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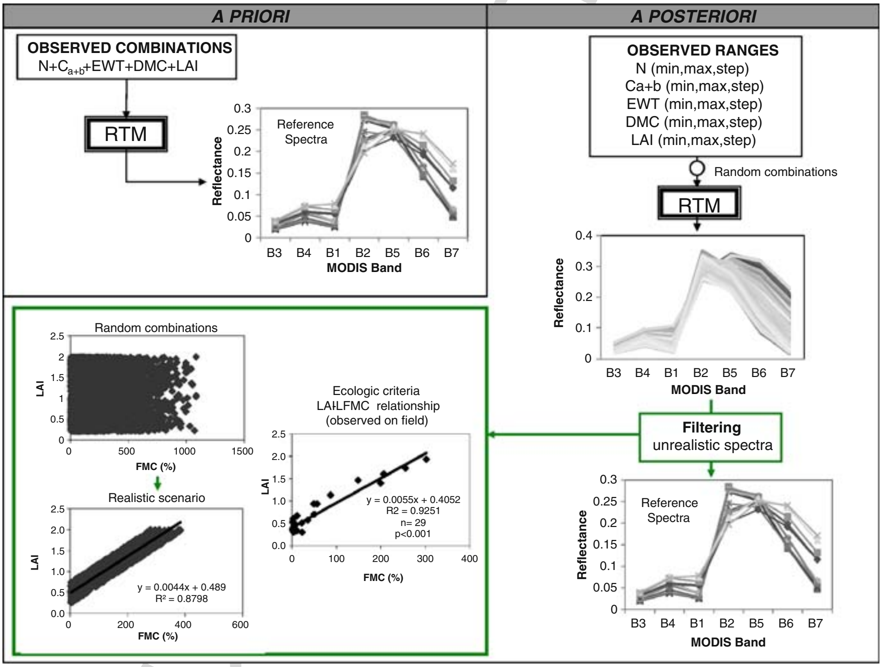


**Fig. 7.2** Ecological criteria can be considered in the inversion of RTM either a-priori or a-posteriori of the use of RTM

species and later designated reduced and realistic co-evolution ranges for the simulations. Using a priori ecological rules in simulation models significantly decreasing the residual estimation error when compared to models run with unrestricted ranges. Another approach is applying those ecological rules after the simulation is done with random inputs, selecting only those combinations that are closer to field conditions (Yebra et al. 2008b).

Most studies based on RTM have found that the Equivalent Water Thickness (EWT) can be retrieved from reflectance data, because it represents the water absorption depth of leaves (Ceccato et al. 2002b; Datt 1999). However, the FMC is more difficult to estimate from reflectance measurements, because it not only depends on water absorption, but also on the changes in the dry matter as it dries. Sensitivity analysis based on a wide range of conditions has found the potential for FMC retrieval from reflectance measurements (Bowyer and Danson 2004), providing that the dry matter content can also be estimated, or otherwise the effect of dry matter on reflectance is masked by the higher absorption coefficients of water (Riaño et al. 2005).

#### 7.2.2.4 Thermal Data

An alternative to measuring moisture content of live fuels relies on thermal infrared sensors. Vegetation temperature is affected by water content, because when plants have water stress they tend to reduce evapotranspiration, and therefore the temperature of the leaf increases (Jackson and Ezra 1985). Because transpiration depends on air temperature, several authors have tried to estimate water stress from the comparison of air and surface temperature. This is the basis of the Crop-Water Stress Index (CWSI) (Jackson et al. 1981), the Stress Index (SI) (Vidal et al. 1994) and the Water Deficit Index (WDI) (Moran et al. 1994).

These indices are commonly based on the energy budget equation, in which the sensible heat flux (H) is inferred from the difference between surface and air temperatures ($T_s$–$T_a$) as a function of the latent heat flux (LE). Cumulative $T_s$–$T_a$ related well to monthly fire start numbers throughout the fire season over Mediterranean forests (Prosper-Laget et al. 1995). For the same ecosystem, Vidal et al. (1994) used the energy budget equation to compute the ratio between actual and potential evapotranspiration (AET/PET) from daily NOAA-AVHRR surface temperatures and synoptic air temperatures, which was related to fire occurrences and to two shrub flammability variables (Desbois and Vidal 1996).

Combining spectral indices with thermal data to estimate LFMC has shown better correlations with water content than using either of the two variables alone (Chuvieco et al. 2004b; Sandholt et al. 2002).

#### 7.2.2.5 RADAR

Active microwave images are very useful to monitor vegetation status of cloudy areas, because these wavelengths are not interfered by atmospheric conditions. Several sensors currently provide RADAR images at a regular basis (ERS,

ENVISAT, RADARSAT. ALOS) and future missions will guarantee a worldwide systematic coverage from microwave sensors. However the use of microwave images for retrieval of plant water content is more complex than with optical sensors, and presents different factors of potential confusion, such as vegetation biomass, height, topographic position or roughness (Beaudoin et al. 1995).

Microwave backscatter is sensitive to the dielectric constant of the surface materials and varies primarily with water content of the plant canopy or soil moisture (Way et al. 1991). Within the microwave spectral region, Leblon et al. (2002) reported significant relationships between rates of change in LFMC and radar backscatter ($\sigma°$) in the boreal forest. The effects of these factors can be largely accounted for in the relationship between rates of change in the backscatter coefficient and rates of change in FMC ($\Delta FMC/\Delta t$), and therefore good correlations can be found in areas where other.

Saatchi et al. (2007) obtained good correlations between SAR backscatter and several fuel parameters using a semi-empirical model to estimate forest biomass ($r^2 = 0.78$), fuel loads ($r^2 = 0.85$), and crown bulk density ($r^2 = 0.84$). There is empirical and theoretical evidence that backscatter data can be used to interpret crop water stress and soil moisture (Du et al. 2000). Nonetheless, radar backscatter depends on the relative positions and spatial densities of the plant canopy constituents and roughness and moisture content of the underlying soil, making it difficult to interpret canopy water content.

## 7.3 Fuel Type Mapping

Fuels are complex in structure, vary widely in their physical attributes and therefore, vary in their potential fire behavior and fire effects. This variation in fuel characteristics is the expression of ecological processes working over time and of human manipulation (Ottmar and Wright 2002). Since the combinations of fuel properties in plant species are almost infinite, the description of these properties relevant for fire danger estimation and fire propagation studies is based on classification schemes, which summarize large groups of vegetation characteristics. These groups are usually called "fuel types" (Pyne et al. 1996). There are several strategies to classify fuel types according to the final use of the fuel classification. For instance, we can distinguish between fire behavior fuel types and fire danger assessment fuel types. The former are more oriented toward fire propagation models, while the latter are designed to determine fire risk conditions. The best known classification strategy is the Northern Forest Fire Laboratory (NFFL) fuel types, initially developed for predicting fire behavior during an on-going wildland fire (Albini 1976). Fuels are organized in four general groups according to the main surface propagation medium: grasslands, shrublands, timber, and slash. An updated version of this classification system has been proposed by Scott and Burgan (Scott and Burgan 2005). A similar approach was taken by the Canadian Forest Fire Behavior Prediction (FBP) system and includes sixteen fuel-type classes to predict fire behavior characteristics such

as fire intensity, rate of spread, and fuel consumption (Forestry Canada Fire Danger Group 1992).

The best known fire danger oriented fuel classification systems is the National Fire Danger Rating System (NFDRS), proposed by the US Forest Service (Deeming 1975). This system used fuel models similar to the NFFL models, but emphasized heavier fuels to account for seasonal drying trends.

Finally, in recent years new fuel classification systems intended for fire effects assessment have been developed. The Fuel Characterization Classification System (FCCS) (Ottmar et al. 2003; Sandberg et al. 2001), generated within the scope of the LANDFIRE Prototype Project (Keane et al. 2006), was developed to create and catalogue fuelbeds and to classify those fuelbeds for their capacity to support fire and consume fuels.

### *7.3.1 Methods to Map Fuel Types*

Methods to obtain fuel type maps are strongly dependent on the use of the final product (Chuvieco 2003). Previous projects have explored the use of different techniques to map fuel properties, most are from extensive field campaigns, remote sensing methods and ecological gradients studies (Giakoumakis et al. 2002; Keane et al. 2001).

#### 7.3.1.1 Field Surveys

Because fuel types are a complex function of vegetation characteristics, field mapping of fuel types is very costly and time consuming. For this reason, field surveys tend to be reserved for validation and fuel parameterization studies.

The first efforts to map fuel types were based on field surveys in the beginning of the twentieth century (Hornby 1935; Show and Kotok 1929). More recently field surveys at regional and continental scales have been conducted in the USA based on statistically developed sampling schemes (Ottmar and Vihnanek 1999, 2000; Ottmar et al. 2001, 1998). Some of these studies generated photo-key guides, where fuel types are described in a qualitative format to aid their classification in the field. Additionally, field measurements of each fuel type are performed to quantify fuel properties. The photo-guides have been widely used by forest managers and researchers in different ecosystems.

#### 7.3.1.2 Aerial Photo Interpretation

The spatial coverage limitations of field work and cost soon made it clear that other methods were required for operational fuel type mapping. The growing use of aerial photography for natural resource mapping during the 1940s and 1950s provided a good alternative to field surveys. Lee (1941) was among the first to propose the use of photo-interpretation techniques to discriminate fuel types in aerial photography,

although he pointed out some limitations as well, such as confusions caused by illumination differences.

The introduction of natural-color and infrared-color photographs increased confidence to discriminate fuel types. For example, Bertolette and Spotskey (1999) used photo-interpretation of infrared-color aerial photographs, combined with extensive fieldwork, to produce a detailed inventory of fuel properties such as canopy cover, tree height, crown base height, and crown bulk density, which are required for the new three-dimensional fire simulation models.

#### 7.3.1.3 Ecological Modeling

Ecological modeling overcomes some of the problems of fuels mapping associated with the obstruction by the forest canopy, limitations of remote sensing products, high variability of fuels, and construction of fuel models (Keane et al. 2002). The ecological modeling approach employs environmental gradients and biophysical modeling in combination with field sampling and remotely sensed data. Environmental data include species composition (e.g., cover type), biophysical characteristics (e.g., potential vegetation type), and vertical stand structure (e.g. structural stage) (Keane et al. 1998, 2002). Using a predictive landscape modeling approach Keane et al. (2006) created maps of canopy fuels. This approach integrates remote sensing, biophysical gradients and field-referenced data to map canopy bulk density and canopy base height. These authors also used a hierarchical set of rules to assign surface fuels models to combinations of LANDFIRE data layers using information stored in the LANDFIRE fuel database.

### *7.3.2 Mapping Fuel Types from Satellite Data*

#### 7.3.2.1 Optical Passive Sensors

Satellite Earth Observation is an alternative method to map fuel types at different spatial scales, because it provides a spatial view of vegetation characteristics. However, only some of the most relevant properties of fuel types can be retrieved from satellite data, and therefore factors of potential noise still remain. Keane et al. (2001) divided the remote sensing methods for fuel mapping into direct methods and indirect methods. The latter approach recognizes the limits of imagery to directly map fuels and consequently, uses other characteristics that can be more easily mapped (e.g. ecosystem characteristics) as surrogates for fuel types. This approach assumes that certain biological properties can be accurately classified using remotely sensed images (Keane et al. 2006).

The utility of remote sensing for fuel type mapping was suggested by Adams (1965) in the early sixties. Kourtz (1977) carried out pioneer work on fuel type classification using digital processing techniques (unsupervised/supervised classifications and principal component analysis) of Landsat/MSS images. The resulting fuel map comprised nine classes. After this initial attempt, numerous studies have

shown the utility of remote sensing methods for fuel type mapping using data from different sensors with varying spatial and spectral resolutions. Most of the efforts have been done using Landsat-TM/MSS data, due to the fact that it provides a good compromise between spectral and temporal resolutions, while covering an area suitable for regional applications (Burgan and Shasby 1984; Castro and Chuvieco 1998; Riaño et al. 2002; Roberts et al. 1997a, 2006b; Salas and Chuvieco 1995; van Wagtendonk and Root 2003).

At regional and global scales low spatial resolution sensors such as NOAA/AVHRR, SPOT-VEGETATION or MODIS have been employed (McKinley et al. 1985; Nadeau et al. 2005; Roberts et al. 2006b; Zhu and Evans 1994). An examples is the 1 km resolution fuel model map developed by Nadeau et al. (2005) for the Canadian Forest Fire Behavior Prediction (FBP) system. This project was developed from three global sources using a fuzzy logic approach. The input variables were the Land Cover classification from SPOT-VEGETATION data (Latifovic et al. 2004), the ecozones and ecoregions of Canada and the National Forest Inventory data.

Optical remote sensing systems have two important limitations for fuel type mapping. First, they are not able to detect fuel height, which is a critical variable to characterize fuel types in most classification systems, and second they are not able to extract information from the understory layer, when the forest canopy is very dense.

Indirect estimations of heights from optical sensors have been approached by several authors, using surrogate variables such as texture and spatial homogeneity. The results were only accurate for some categories (Riaño et al. 2002).

The limitation of optical wavelengths to discriminate optical wavelengths is difficult to overcome, since the penetration capacity depends on leaf transmissivity and leaf area index. Most remotely detected reflectance comes from the upper canopy, and therefore little or no information on the surface conditions is available. A few authors have tried to discriminate forest understory, and only indirect methods have been proposed (Stenback and Congalton 1990).

New hyperspectral and hyperspatial sensors also have been tested for fuel type mapping. These sensors provide good results when the resolution is fine enough compared to the crown spatial density. For instance, the airborne AVIRIS imager (with 224 bands) has been used for the spectral characterization of fuel types (Roberts et al. 1997a). A recent study in central Spain has shown the potential of using object-oriented classification for improving the definition of fuel types in high spatial resolution Quickbird images (Arroyo et al. 2006, 2008).

#### 7.3.2.2 LIDAR Data

The importance of estimating heights in the description of fuel properties has led to the use of new remote sensing techniques which are better suited to generate this variable. This is the case of the Lidar systems which provide a recording accuracy in height estimation of up to 5–15 cm (Baltsavias 1999).

Most Lidar systems are airborne and therefore only suitable for local coverage. The most extended airborne LIDAR is the small footprint-discrete return acquisition system (usually the first and the last pulse are recorded). Several studies have shown the potential of these data for describing crown height, crown base height, and crown bulk density (Morsdorf et al. 2004; Riaño et al. 2004, 2007a, 2003).

Understory canopy height is difficult to obtain from large footprints LIDARs, but small footprints LIDARs have provided reasonable results (Riaño et al. 2004). Bare ground is mixed with surface canopy signals on steep slopes due to the spreading of the ground return in large footprints full-waveform (Riaño et al. 2007a).

The launch of the first LIDAR satellite, named ICESat, opened new possibilities to derive fuel properties at global scales. Aboard ICESat was the Geoscience Laser Altimeter System (GLAS) designed for ice monitoring It also provides the potential to estimate vegetation parameters (height, aboveground biomass, etc) with good accuracy in flat terrain (Lefsky et al. 2005; Simard et al. 2008; Sun et al. 2008). An ICESat-II is expected to be launched by 2010–2013. A revolution in terms of three dimensional assessment of the vegetation at global scale will come if the NASA mission DESDynI to be launched 2010–2013 is successful (http://desdyni.jpl.nasa.gov/). It is a combination of an infrared LIDAR system (˜1,064 nm) with a 25 m footprint and a 1 m vertical accuracy, together with L-band Interferometric Synthetic Aperture Radar (InSAR) system with multiple polarization. InSAR will be calibrated with LIDAR data, and also depending on polarization InSAR penetrates to the ground or provide information of the canopy.

#### 7.3.2.3 RADAR

Radar data have also provided complementary information to optical sensors for fuel mapping, because radar is very sensitive to temporal and spatial variation of the canopy biomass (Beaudoin et al. 1994). Several projects based on ERS-1, JERS-1 and Radarsat data have been undertaken to predict forest attributes that are critical for fuel type mapping, such as foliar biomass, tree volume, tree height and canopy closure (Hyyppa et al. 2000; Ranson et al. 2001).

Difficulties of estimating precisely canopy height, prevent the use of RADAR images for biomass estimation (Hyyppa et al. 2000). However, new recent approaches have greatly improved these studies, using interferometric and multi-frequency techniques. Interferometry is based on observing, simultaneously or very close in time, the same area with two microwave antennas, deriving information on terrain heights or movements from interferences between the backscatter coefficients of the two signals (Madsen and Zebker 1998). Interferometric measurements may be complemented to LIDAR data to improve estimation of vegetation height (Slatton et al. 2001). Multiband and multipolarization RADAR systems are also providing sound information for fuel geometrical description, since microwave penetration in vegetation canopy is wavelength-dependent. Shorter bands (X-C) mostly backscatter from the upper canopy, while longer bands (L-P) return mainly from the lower branches and the forest floor.

## 7.4 Conclusions

Fuel moisture status and fuel geometrical properties are critical for fire danger estimation. New methods and new data sources for retrieval of those properties are required to improve spatial and temporal monitoring of fire danger. Current satellite-borne sensor systems provide reasonable accuracies for estimating fuel moisture content, using different absorption bands in the optical domain and thermal properties, while the retrieval based on microwave images needs additional assessment. Regarding fuel type mapping, optical sensors provide accurate results to discriminate some fuel parameters, but still active sensors (mainly Lidar, but also RADAR) are required for a better characterization of fuel heights, biomass and density.

# Chapter 7

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# Chapter 8
# Impacts of Fire on Society: Extreme Fire Propagation Issues

**Domingos X. Viegas, L. M. Ribeiro, M. T. Viegas, L. P Pita, and C. Rossa**

**Abstract** Human activities namely forest management interact with natural conditions to determine fire occurrence and fire impact in a complex form. Climate change tends to facilitate even larger and more dangerous fires. The wildland urban interface is an emerging problem derived from the expansion or urban areas associated to high risk fire conditions. Extreme fire behaviour in the form of eruptive fires, crown fires and spot fires are associated to great damage to the environment and to loss of human lives. Some cases of fatal accidents that occurred recently in Europe are presented to illustrate the proposed concepts.

## 8.1 Introduction

Fire is part of Nature and during millennia ecosystems have been shaped by its presence and evolved having fire as one natural factor, like climate, vegetation and topography. Since long Man uses fire to shape Nature and also tries to manage Nature with the purpose of controlling the role of fire. Quite often the un-careful use of fire, for example in rural activities, can produce an unwanted fire that we designate as a forest fire regardless of the type of vegetation that is involved in its propagation. In modern societies forest fires are perceived as a component of non controlled environment like the designation of "wildfires" expresses. As such it is considered that all fires should be avoided and banished, just like modern civilization was able to eradicate some plagues or diseases. The complete exclusion of fire from the environment is not possible and it is not even desirable.

Human activity interacts with forest fires in many ways and at different stages of the problem of fire management: before, during and after. It is interesting to notice that among all natural disasters forest fires are the only ones in which human

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intervention can change in a decisive way, its evolution and outcome. For many reasons we can even say that Humans are usually at the beginning and at the receiving end of forest fires.

The way in which society is organised and structured, what vegetation types exist and how it grows, how land is used and managed, and the development of fire prevention structures determine, in an important form, the seasonality, number, frequency, extension and type of fires that may occur in a given region for normal weather conditions. Very often, fires are caused directly by human action, either intentionally or by accident. This is particularly true in Mediterranean regions.

Fires destroy directly the forest and the natural environment but they also affect the socio-economic activity. In the limit fires put in danger the health and the life of persons living, working or just visiting fire prone areas. During recent years the increasing extension of urban areas mixed with rural or forest areas associated with a marked increase of fire activity make this impact even greater.

Fatal accidents associated to forest fires remain in the memory of the society much beyond other losses. As a consequence the lack of security that they generate has great impact in the attitude of society towards forest fires.

One of the consequences of climate change is the modification of the expected fire behaviour (Viegas 2007). This reflects both in the occurrence of larger fires and larger total burned areas at the end of each season, and also in the increasing frequency of extreme fire behaviour occurrence. This worldwide tendency is becoming clearer in the last decade as was observed in Portugal in 2003 and 2005, in France in 2003, in Spain in 2006, in Greece in 2007 and also in the USA, namely in California in 2007 and 2008.

In Mediterranean climate forest fires can propagate in the following types of extreme regimes: (i) eruptive fires; (ii) crown fires and (iii) spot fires. Conditions associated to each one of these fire regimes are described. Particular attention is given to eruptive fires in which fire accelerates very rapidly, as they are associated to the majority of fatal cases of accidents occurred in forest fires. A fire eruption is usually associated to particular topographic features but it may happen also under certain wind conditions that are described.

Some case studies of extreme fire related accidents in which single or groups of persons lost their lives are described to illustrate the relevance of the concept of eruptive fires. The impact of these extreme fires on the safety of civil and operational personnel and the consequent demands on forest planning are addressed.

## 8.2 Society and Fire

Fires are perceived by society as one of the major natural disasters in several regions of the World given their frequency, extension and damaging effects. In present conditions of climate change due to global warming many countries are facing larger and more intense fires, more extended fire seasons and an increased inter-annual variability of fire occurrence conditions. Some regions that did not face the problem

of forest fires in the recent past are now having it. Many societies are well prepared to manage forest fires in low to medium meteorological risk conditions but when these become extreme it is very difficult to control the fires.

Fire risk perception varies from one society to another and in the course of time, depending on the contact and knowledge that people have on forest fire related issues. The concepts of high fire risk or of a large fire are not the same for persons living in a fire prone region or for persons that are less familiar with this reality.

The use of fire in rural activities is considered as a risk and therefore it tends to be banned in many countries at least in some periods of the year. In the limit society tends to be in favour of fire suppression policies but it is recognized that if this policy is not accompanied by other complementary activities to manage and reduce vegetation biomass in the forest the exclusion of fire will only contribute to create greater problems in the future.

One of the forms to reintroduce fire in the rural environment is through the use of prescribed fire. This technique is employed to burn selected areas of the forest in periods of the year, in meteorological conditions that maximize the possibilities of fire control and minimise side effects on the vegetation and on other components of the ecosystem. One of the drawbacks of prescribed burns is the production of smoke and the fact that biomass is being burned with no use. For these reasons the extensive use of prescribed fire must be addressed with caution in the context of the overall climatic and carbon cycle. Maybe society will have to return to the use of the available biomass to produce energy and to reduce the risk of fire.

Returning to the concept of large fire we cannot give a unique definition for it. As was said above the perception of a large fire varies from one region to another. For example if we use the burned area to define it there may be different limits, like for example 500, 1,000 ha or even 10,000 ha, depending on the local context. On the other hand if we consider those fires in which there was loss of human lives they remain in the memory of the societies. Regardless of the size of the fires that originated those losses are remembered as very large and important events in contrast with fires that actually destroyed much larger areas.

## 8.3 The Wildland Urban Interface

The problem of wildfires in the Wildland Urban Interface (WUI) is not new but its importance is growing quite rapidly in recent times due to several factors. The reasons for this increase are multiple and interact with each other in a complex way. On one side climate change and global warming with more frequent dryness periods and heat waves facilitate the development of very large fires that easily reach the WUI. On the other side in order to be competitive, and profitable, agriculture needs to be industrialized in large areas and associated with mechanized production practices requiring fewer workers. Therefore modern societies tend to concentrate in the cities, leaving behind old practices of traditional agriculture and land management and increasing the population of the urban areas that grow into previous

agricultural or forested areas. A third factor is the aging of the rural population that sometimes live in isolated houses or dwellings and have no capacity to protect themselves. Another factor is the trend to have secondary houses or to spend vacations in rural areas that puts people not familiar with fire risk conditions in face of problems that they are not prepared to address.

With the joint effect of these factors we have to deal with an increasing problem of fire reaching populated areas. As these fires are usually associated to potentially important loss of valuable property, disruption of socio economic activity and risk to human health and life they deserve a particular attention. Forest fires have no barriers when they spread. Some agricultural areas that used to form protection belts around villages no longer exist with land abandonment. As a consequence fires do not stop at houses or dwellings. Whenever there are social, industrial, recreational or other human structures in danger the defence priorities of the civil protection forces in charge of suppressing the fire changes. Usually fire fighting concentrates on defending those assets, leaving fire to propagate freely in the forest and putting in risk even larger areas. Whenever meteorological conditions assume extreme values the risk raises exponentially, as there is a strong possibility of having multiple fires that spread with great intensity and jeopardize the capacity of the fire suppression forces. In these conditions fires can easily reach the WUI, endangering several isolated houses, villages or even large cities.

In many regions like in Southern Europe the construction materials used for housing are very resistant to fire and therefore they constitute in principle a good shelter place for residents. On the contrary when houses and structures are built with wooden material they are flammable and do not offer good protection. In this case each new house means added fuel in the environment. Even fire resistant houses when exposed to intense fires can burn due to weak points in their structure or boundary. This is the case for example of doors, windows, shades, ducts and roof elements.

One of the issues with the WUI is the decision of residents to stay and defend their houses or to leave. This decision depends very much on local tradition that determines the attitude of the population and of the authorities and of course it depends very much on the particular conditions of the fire and of the urban settlement. In principle children and disabled persons must be evacuated with great anticipation to avoid problems in the escape routes. A large number of accidents with civilians actually occur when they decide to leave their houses at a very late stage and are caught by smoke or fire in the open space, sometimes not far from their home. Very few persons have died in Europe in their houses during a forest fire. Houses are much better defended if residents stay and have the support of fire fighters but this is not always possible. Therefore a certain degree of auto defence preparation must exist in WUI residents.

The defence of the WUI poses important problems to fire fighting forces as they have to deal not only with forest fires and with simultaneous structural fires but they have also to manage residents sometimes in panic or with other sort of difficulties.

Smoke is a major nuisance during forest fires due to its impact on visibility, respiratory capacity and comfort. In the long term it may affect the health of persons

exposed to it. In the WUI the presence of smoke is particularly harmful during operations both for residents and for fire fighters. In some cases smoke can remain in the area for several days disrupting ground and aerial transportation and several other activities, as was the case of Indonesia in 1997 (SCHWELA 1998).

Any citizen living or travelling through a rural area might be in risk of being involved in a forest fire especially at the WUI. For this reason we consider that the problem of the WUI requires a collective approach from the authorities, planners, managers, researchers and population.

The fire seasons of 2003 and 2005 in Portugal, with the loss of 43 lives, and the fire season of 2007 in Greece, with 78 dead, are a strong alert message to the importance of the problem.

## 8.4 Extreme Fire Behaviour

The way forest fires spread or behave is of great importance to assess the possibility of controlling them or to estimate the potential damage that they can produce to the environment. When the rate of spread of the fire and the energy released by the flame front are low it is possible to control the fire and even suppress it with normal means without major problems of safety. On the other hand there are some fire spread conditions that make fire control very difficult and dangerous. We designate these conditions as extreme fire behaviour and we consider that there are the following three types of extreme fire behaviour:

- Eruptive fires
- Crown fires; and
- Spot fires.

We shall describe briefly each type of extreme fire behaviour, the conditions in which they can occur and their risk to the natural and anthropic environments.

### *8.4.1 Eruptive Fires*

In the majority of fire behaviour studies and analysis it is assumed that for a given set of values of the following parameters: (i) fuel bed properties, (ii) topography configuration, namely terrain slope, and (iii) meteorological factors, particularly wind velocity, there is a unique value of the rate of spread. This concept is traduced in the well known triangle of factors of fire. This concept corresponds to a static approach of the fire behaviour problem and it is a non correct simplifying assumption that is not valid in the majority of cases (cf. Viegas 2006). It was shown that the fire has a dynamic behaviour due to the convective flow that is induced by the fire itself. This flow modifies the boundary conditions near the fire front and therefore changes

the rate of spread of the fire even if the set of the above mentioned factors remain constant.

If a fire spreads in a slope or with favorable wind the result of this induced flow is a continuous acceleration of the ROS. This process is particularly intense and fast in canyon shaped terrain as was shown in Viegas and Pita (2004). We consider a canyon or ridge a terrain configuration that is composed by two slopes that intersect forming a line that we designate by “water line” as quite often it gives support to a course of water.

In Viegas (2005) the designation of “eruptive fire” is proposed to this fire behaviour given its analogy and resemblance with a volcanic eruption. In that study a mathematical model to predict the ROS variation with time in this type of fires is proposed. According to this model after a certain period of time the ROS increases reaching very large values that are not predicted in current fire behaviour models, namely by Rothermel model (cf. Rothermel 1972, 1983). The period of time required for a fire to erupt depends on the terrain configuration, on the wind flow and on the fuel bed properties.

In Viegas (2006) the parameters associated to various types of fuels are proposed and their influence on eruptive fire behaviour is discussed. These results are summarized in Fig. 8.1 where it is shown that herbaceous fuels have a characteristic time of the order of one or two minutes, while shrubs have a response time of the order of 15–20 min. This result is consistent with what is observed in many real cases like the ones described below and also in the cases of Mann Gulch, the Storm King and the Freixo accidents that are well documented in the literature (cf. Viegas 2005).

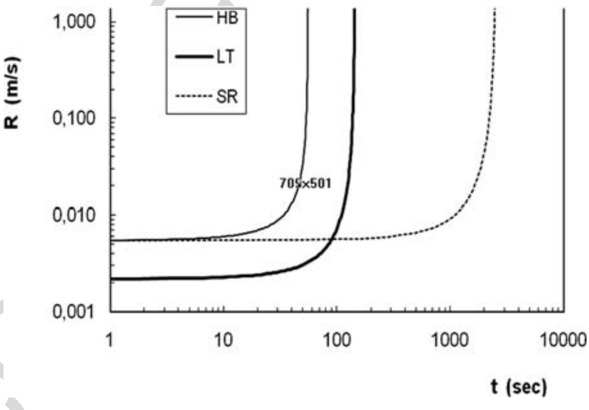


**Fig. 8.1** Rate of spread evolution as a function of time in a fire eruption for three typical forest fuels: (HB) Herbaceous; (LT) Litter and (SR) Shrubs

One relevant aspect of eruptive fires is that they actually do not depend on atmospheric conditions but rather on terrain configuration and on fuel bed properties. The occurrence of eruptive behaviour is also not very much dependent on the moisture content of the fuel bed. For these reasons eruptive fires can be very dangerous as they can be deceptive and surprise even experienced fire fighters with their sudden change of behaviour. The fire induced modifications of the atmospheric conditions

can be overwhelming and even overcome strong contrary winds as were the cases of Loop Fire (Countryman et al. 1968) and Freixo (Viegas 2005).

Eruptive fires can also occur in flat terrain induced by wind. If wind velocity and direction remain relatively constant during a period of time a spreading fire can also experience a continuous increase of the rate of spread even on relatively flat terrain. Examples of such fires are Sundance (Anderson 1968; Finklin 1973) and Vidauban (Alexandrian 2004).

### *8.4.2 Crown Fires*

The second type of extreme fire behaviour corresponds to the occurrence of crown fires, which are those that extend from the surface to the higher strata of the tree fuels, i.e. the canopy fuels. The transition from surface to crown fires depends on the intensity of the surface fire (amount of energy released per unit of time and per unit of fire line length), on the fuels between the surface and the canopy base, the so called transition fuels, and on the canopy properties. According to Van Wagner (1977) they can be classified as passive, active or independent. In a passive crown fire the canopy fuels do not form a continuous fire line and may burn only partially, and the general fire behaviour depends essentially of the surface fire. In an active crown fire the canopy fuels burn as a continuous fire line and the fire behaviour depends mainly of the crown propagation. In an independent crown fire the fire spreads only in the canopy fuels and not in the surface fuels, although this type of propagation is rare and happens only for short periods of time and under extreme wind and/or steep slopes (Beck et al. 2005).

Crown fires are extremely destructive due the very large energy that is released at the fire front, with flames as high as 30–60 m and ROS of the order of 10–15 km/h as these fires tend to be accompanied by very strong winds that are felt on the top of the canopies. Given the strong convection processes that are associated to this type of fires they can easily produce spot fires that are described below.

### *8.4.3 Spot Fires*

Combustion of natural vegetation produces particles of different sizes that are released from the reaction zone and can be transported by the convection column and by the wind flow. When these particles fall on vegetation they can produce a new fire ignition or spot fire.

The mechanisms of spot fires are complex and poorly understood. The occurrence of a spot fire can be divided in three main steps. First the ember is generated in the combustion reaction of the main fire and is elevated in the fire plume getting exposed to a higher ambient wind velocity, as wind increases with height; afterwards the ember travels, driven by wind, and losing height. Finally the ember reaches the ground possibly igniting the fuel and causing a spot fire. Each one of these steps

depends on such a large number of parameters that many studies deal with this problem as a stochastic process and propose to estimate the probability of occurring spot fires or the probable maximum distance.

According to McArthur (1967) spot fires 8–10 km ahead of the main fire front are common in high intensity fires burning in Eucalyptus. In March of 1965 in Gippsland, Victoria, a spot fire was registered 29 km ahead of the main fire front. Long distance spot fires create problems to fire management as the new fires that they initiate require a change of strategy and a diversion of resources from one area to another. Spot fires can easily cross fire breaks, making them less efficient in such conditions and can even reach areas that might be otherwise well protected against a surface spreading fire. Another situation is associated with spot fires in the WUI where even areas that were managed with fuel reduction treatments can be reached and endangered by spot fires. This is the case for example of large cities that may have vulnerable sites, like parks or gardens, in its interior that can be ignited by spots.

Short distance spot fires interact with the main fire, increasing the fire rate of spread, and end up merging with the fire front. Medium to short distance spot fires are particularly dangerous for the safety of fire fighters and other personnel at the fire front since they can be trapped between the fire front and the spot fire. Quite often short distance spot fires consist in multiple spot fires which makes the situation even more dangerous.

## 8.5 Some Cases

In fire management above all aspects the protection of human life is a top priority. Society expects that all undesired fires are extinguished as soon as possible. A policy of let burn is unlikely to be applicable in European Mediterranean regions due to the extensive areas of WUI and human presence. Consequently there are groups of persons that are especially trained and equipped to fight and suppress the spreading fires. With present day technology the capacity of these fire fighting crews is quite high but it is limited and they can deal only with low to medium fire risk conditions. When risk conditions become very high in a section of the fire – with crown fires for example – it is not possible technically to attack it directly and the personnel must back up for an indirect attack. These situations per se do not pose great safety concerns.

Although crown fires are extreme fire events where we can have rates of spread up to 12 km/h and flame lengths up to 200 m (Beck et al. 2005) most of the deaths caused by forest fire burnovers take place in small fires or on isolated sections of large fires (NWCG 1996) when fires erupt, usually on canyons or steep slopes (Viegas and Pita 2004). The worst situations occur when the behaviour of the fire changes rapidly and its ROS grows larger than the capacity of the personnel to outrun it. These conditions are unfortunately met when there is an eruptive fire. Although there are many cases described in the literature of such cases, including

those that were mentioned above, we shall present some cases that occurred recently in Europe to better illustrate our concepts.

### 8.5.1 Guadalajara

On the 16th of July of 2005 in Riba de Saelices, Guadalajara (Spain) at around 15 h embers driven by wind from a barbecue, ignited a field of stubble and initiated a fire that would last four days, destroyed more than 12,000 ha and caused the death of eleven fire fighters (Viegas et al. 2005). This fire occurred in a period of severe drought and on the day it started, the temperature of the air was 30°C and the relative humidity was of the order of 25%. Maximum wind velocity registered in the area was of the order of 60 km/h blowing from East/Northeast. The area has a complex topography with agricultural fields – cereal crops – in the valleys and pine and shrubs in the mountains.

On the 17th July the fire was out of control and its West flank was endangering the village of Santa Maria del Espino. A group of fire fighters engaged the mission of protecting this village. This group was composed by twelve persons that were carried in five vehicles: three jeeps and two fire trucks with water supply.

At around 17:00 h the group drove from Santa Maria del Espino along a forest road towards the ridge of the mountain in direction of the fire. At 17:20 h and after assessing the situation the group stopped in a pine stand and started to attack the flanking fire.

Unknown to them a fire had started in the valley below them – probably caused by a spot from the main flank – and produced a violent eruption in a pine stand in the slope that was at the right hand side of the group. Having this sign of danger indicating that conditions were changing the group decided to back up using the same road that brought them in. The group leader departed in his jeep followed immediately by the second jeep that carried the two members of the crew of one of the fire trucks. The third jeep carrying seven fire fighters departed seconds later. The driver of the second truck was the last to leave the scene and when he tried to follow the group with his vehicle he was surrounded by smoke and lost control of the truck (Fig. 8.2).

We now know that if the group had the possibility to drive around 1.5 km along the road in a run that would take them less than five minutes to make, they would reach safety. Unfortunately for them a second fire eruption occurred on the other slope of the canyon below them on the left side of their escape route just when they had entered their vehicles. In few seconds all this road was full of smoke from this second eruption that impaired visibility and probably even stopped the engines of the vehicles. The occupants of the two first jeeps left their cars trying to run on foot but they did not manage to go very far. The driver of the third jeep still tried to run away from the eruption that was in front of them and went off the road driving towards his right side towards low shrubs and small rocks. After a while he turned left following a path parallel to the main road but suddenly the car crashed against

**Fig. 8.2** General view of the site of the accident of Guadalajara. The three vehicles in the photo transported eleven fire fighters that were trying to escape from the fire. The fire erupted in a canyon to the *right* of the photo below the pine stand where they were fighting a flanking fire

a wall made of loose stones and immobilized the vehicle. Five of its occupants still left the car seeking refuge near the stone wall but they all perished there.

The driver of the second truck, who was the only survivor, had to jump from his car when he felt that it was going out of the road and into a ravine. Although he was injured in the fall he managed to crawl till he reached the other truck and laid on the ground below it. Fortunately for him there was practically no vegetation in that area so in spite of the intense heat and smoke this man was not caught by the flames and survived.

### *8.5.2 Famalicão*

This accident happened during the summer of 2006, on the 9th of July in Central Portugal, nearby a small village named Famalicão da Serra. During this fire, six fire fighters lost their lives, one Portuguese volunteer from the local headquarter and five Chilean professional fire fighters from a helicopter transported fire brigade that were working for a private company in charge of protecting plantations explored by cellulose plant companies.

The fire was caused by negligence when a forest worker was cutting herbs and shrubs in a farm at the base of a slope. In the early stage of the fire, the land owner and the worker tried to stop the fire with a fire extinguisher, but unfortunately they did not succeed, and lost the control of the situation. The fire alarm was given at 12:24 h, and the accident happened one hour and half later.

During this day the temperature was about 35°C and the relative humidity was 15%. The fuel type in the area of the accident was manly composed by *Pinus pinaster, Aiton sp.* stands with some shrubs undercover (Rossa and Pita 2006). The moisture content of dead pine needles at Lousã on that day was 13.5%.

The local fire brigade did not manage to stop the fire at a road some meters above the origin and the fire continued to spread upslope to Northeast. One initial attack fire crew, transported by helicopter from a nearby base, arrived at 12:45 h. They landed at the base of the fire and tried to suppress its East flank with limited success. In the meantime the head of the fire had crossed a fire break at the middle of the slope and entered a mature pine stand on its top. Some fire fighters and civilians moved to that area attempting to protect the pine stand. The helicopter with the Chilean brigade arrived at around 13:20 h and landed on a fire break near the top of the mountain. After assessing the situation the group entered the pine stand started to attack the West flank of the fire below them with hand tools. A volunteer fire fighter from the local fire brigade was instructed by his Commander to help them. The six men were advancing rapidly down slope suppressing a straight line flank fire in pine litter without perceiving (not knowing) the danger that was below them.

Suddenly the fire erupted at the edge of the pine stand below the group and made two or three runs as a crown fire into the stand. The persons that were on the top of the ridge ran away, mostly to the East side, many of them with great difficulties and some even with minor burns.

The six men group inside the pine stand decided to escape to the West side along a road that descended towards the village. Although this route took them far from the fire it also drove them to the water line of a large canyon above the fire.

Practically since the fire start the west flank of the fire near its origin was not controlled and it continued to spread against the wind in the direction of the water-line of the canyon formed by the slope in which the main fire was propagating and an East facing slope (see Fig. 8.3). When the fire reached the water line it erupted in the East face of the canyon and cut the escape route of the group when it was reaching the waterline. At this point the five Chilean fire fighters dropped their tools and started to run up hill in an attempt to escape from the fire. The Portuguese fire fighter decided to stay in an open space created by the fire break and laid in a ravine at the edge of the road. The six men perished when the fire front reached their position.

### *8.5.3 Artemida*

During the summer of 2007 Greece was affected by the worst forest fires of its modern history with more than 270,000 ha burned and with the loss of 78 lives due to forest fires, most of them civilian. Many accidents were associated to fires reaching the WUI with residents trying to flee at the last minute without any support or guidance. One of the accidents that contributed to this toll was the one that occurred near the village of Artemida, in Olimpia on the 24th of August.

**Fig. 8.3** General view of the accident of Famalicão area. The fire started at the *low centre* and spread towards the *top right* corner of the photo. The fire fighters were fighting inside the pine stand in the top centre of the photo, near the edge of the unburned pine strip. The fire spread very rapidly on the slope at the *left* side of the canyon and caught the six men in the middle of the canyon

A fire started on that day in a small settlement of Paleohori at the bottom of a valley, at around 14:40 h caused by outdoor cooking. Forced by strong wind the fire spread very rapidly through the valley where the vegetation – mostly herbaceous, agriculture plots and light forest – was extremely dry. The fire reached very quickly the village of Artemida and its population was ordered to evacuate. A group of around 30 persons, including entire families, left their homes and in their cars they took the road to Zaharo. After few kilometers the road was cut by the spreading fire and they returned to Artemida. At a certain point they met a fire truck that had come to rescue their village. With no place to go the group remained in the road counting with the support of the fire fighters. But when the fire in the valley turned upslope in their direction it came with such violence that the fire fighters were not able to stop it or to give protection neither to the group nor to themselves. Even before the fire arrived some persons had decided to run away from the road through the agricultural field but they also were caught by the racing fire few hundred meters away. Twenty seven persons died at this place making this one of the worst accidents in history. (cf. Xanthopoulos et al. 2009)

### 8.5.4 Kornati

On the 30th of August of 2007 at Vrulje bay a fire was started by accident by a careless smoker in the island of Kornati in Croatia. With severe drought conditions

the light vegetation – herbaceous and light brush – that covered this island was very dry. The strong Jugo winds blowing from Southeast that were felt on that day pushed the fire to Northwest. More details on the ambient conditions during this accident can be found in Viegas et al. 2008.

Several groups of fire fighters were dispatched from mainland to suppress the fire. They were transported in heavy helicopters. A group of 13 fire fighters was lifted from Sipnate bay near the West tip of the island and were in charge of fighting the left flank of the fire on the ridge above Sipnate canyon. Their helicopter transported a collapsible water tank that was put on the ground near the ridge. As there was no space for the helicopter to land and drop the crew at the same spot they were dropped at another site on the ridge 1 km apart. After landing the fire fighters started to walk in direction of the water tank. With the difficulty of the terrain and with the load of their gear this walk was very difficult. Besides this the advancing fire cut their shortest path and forced the group to go down slope and enter the Sipnate canyon in their attempt to reach the water container.

In the meantime the edge of the fire had entered the bottom of Sipnate canyon and was starting to spread upslope along its waterline. Given the configuration of the terrain the group could not see this. At a certain point the group was almost at the water line of the canyon when they saw the fire coming from the bottom of the canyon towards them. Part of the group remained where they were but others dropped their gear and started to run uphill in the very difficult terrain. There was only one survivor from all the elements of the group in the accident that was the most terrible in the history of Croatia.

## 8.6 Conclusion

Forest fires have a great impact on society and all trends indicate that they will have even a greater role in the future in shaping rural activities, forest management and the presence of persons at the interface with the forest. Besides and above the wildland urban interface we have to face the “wildland human interface” in the sense that persons and their safety must have the priority in all fire research and management programs. We showed that extreme fire behaviour namely eruptive fires are associated to a great number of fatal accidents in the past.

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# Chapter 9
# Effects of Fire on Vegetation, Soil and Hydrogeomorphological Behavior in Mediterranean Ecosystems

**Fernando Pérez-Cabello, María Teresa Echeverría, Paloma Ibarra, and Juan de la Riva**

**Abstract** In the Mediterranean context, wildfire has ceased to be a natural ecological factor and has become an anthropic factor of frequent and intense occurrence. Fires cause environmental alterations based the disappearance or modification of the vegetation cover, soil changes and soil hydrogeomorphological behavior. These transformations are mainly concentrated in the immediate aftermath of the fire and are closely linked with fire frequency, fire severity and the period of the year in which the fires occur. A systematic outline of the effects of fire and the factors implicated in the post-fire environmental dynamic is offered. The role of remote sensing methods on fire effects is well known; this chapter also refers to experiences and works on monitoring temporal patterns of vegetation recovery and mapping erosion-sensitive areas

## 9.1 Introduction

In terrestrial ecosystems, especially Mediterranean ecosystems, fire is considered to be a natural ecological factor (Le Houérou 1973, 1993; Naveh 1975; Naveh and Lieberman 1984). It was in the Neolithic that humans began to use fire as a tool for increasing land area for cultivation and pasture by eliminating natural vegetation by means of more or less controlled fires.

The origin of the great diversity of the Mediterranean landscape is found in an irregular climate and a notable topographic variety which humans, as livestock and arable farmers, diversified (Cerdà and Bodí 2007) by building terraces for hillside farming, burning vegetation cover or felling forests to increase cultivation areas and pastureland (Pausas and Vallejo 1999). This dynamic, that became commonplace throughout Europe in the 16th century (Kosmas 1996), reached its peak with the

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demographic explosion of the 18th and 19th centuries when human pressure on the territory intensified and humans even began to occupy marginal terrain.

In the last decades, Mediterranean forests of Kermes oaks, Holm oaks and Savins have been replaced by other communities, mostly *Pinus halepensis* and *Pinus pinaster,* conifers that colonise abandoned agricultural land and are favoured for both reforestation and timber exploitation (de la Riva 1997). The process of abandoning traditional agricultural land is followed by the development of scrubland through the establishment of pyrophytes such as ericaceous and *Cistus* that corroborate the existence of anthropic fires and reduce landscape diversity.

Wildfire has ceased to be a natural ecological factor and has become an anthropic factor of regular and intense occurrence. Fire frequency has increased in some Mediterranean areas in the last decades (Moreno et al. 1998) alongside a simultaneous rain precipitation concentration (De Luis et al. 2000, 2009). Both factors can have a synergic effect on soil degradation.

The main causes of the fires are lightning, volcanoes and human activity, the latter being especially important in the densely populated Mediterranean basin; according to the FAO (2001), approximately 50,000 fires affected 600,000 ha of forest and other vegetation types in the Mediterranean basin every year in the decade of the 1990s.

Fires in Mediterranean ecosystems tend to occur during the summer months of high temperatures and raised levels of evapotranspiration. This is followed by autumns of intense precipitation which causes soil losses. A sharp increase in temperatures, alterations to vegetation cover, nutrient losses caused by translocation and volatilization and the emission of carbon dioxide into the atmosphere are some of the processes that are set in motion by a fire. This leads to changes in the structure and composition of the vegetation and soil, a reduction in infiltration, increased runoff and the loss of nutrients and sediment. In short, there is an increased risk of landscape degradation, a risk that is particularly serious in Mediterranean ecosystems.

## 9.2 The Effects of Fire on Vegetation

The effects of wildfire on vegetation are most evident due to plants & apos; vulnerability to burning and the dehydration processes caused by the heat of the fire. Major degradation tendencies in the medium and long-term may include permanent changes in the composition of the vegetation community, decreased vegetation cover, biomass loss and the alteration of landscape patterns. Wildfires may also induce long-term changes in the floristic and physiognomic parameters of vegetation through their impact on soil physico-chemical properties and plant nutrient availability.

However, it must not be forgotten that fire is the major force in the biological evolution of Mediterranean biota (Naveh 1989). Most Mediterranean plant species exhibit effective regeneration mechanisms for overcoming the immediate effects of

fire (Mooney and Hobbs 1986). In fact, fire may be the only way to ensure natural rejuvenation or long-term biological productivity (Naveh 1989).

Plant species mechanisms can be passive (e.g. thick insulating bark), or active (e.g. re-sprouting from underground storage organs and seedlings from fire-protected seeds). Active mechanisms may lead to a rapid process of vegetation covering with similar characteristics to the previous communities. In Mediterranean ecosystems, such direct succession is known as an autosuccessional process (Hanes 1971; Papiò 1988; May 1991). Direct reestablishment is common and is an example of the resilient nature of ecosystems.

Nevertheless, the response of vegetation to fire is very complex and it is not easy to generalise. The regeneration process is highly variable because of the large number of factors involved: topographic-climatic influences; plant composition (species existing prior to fire in each community); topographic parameters; soil characteristics; land-use history; wildfire severity; fire frequency; post-fire management; post-fire climatic conditions etc. Without attempting an exhaustive revision, the next paragraphs present general descriptions of vegetation traits and the role of environmental factors that have been taken from different research studies and papers.

### *9.2.1 Plant Traits*

Plant species react to fire through different morphological and physiological traits. Some can survive during fire due to thick bark protecting plant tissues or by means of lignotubers (underground storage organs) sprouting and high growth rates after fire. Others can rapidly establish seedlings, taking advantage of post-fire conditions (Buhk et al. 2007). There are many published papers, works and studies that have described regeneration mechanisms (e.g. Martínez-Sánchez et al. 1995, 1999; Daskalakou and Thanos 1996; Thanos et al. 1996; Ne'eman 1997; Pausas et al. 2003; Ne'eman et al. 2004).

In studies analyzing fire consequences on vegetation, the dichotomy between resprouters and seeder species is considered as an important concept (Pausas et al. 2008). Resprouting ability is a very common survival strategy in Mediterranean ecosystems (Konstantinidis et al. 2006). Most sclerophyllous shrubs and trees in Mediterranean areas are resprouters (Naveh 1989) and they are very resilient. Fire may almost completely destroy the aerial fraction of the plants but belowground structures (rhizomes, roots) survive because of the low thermal conductivity of soil. After the fire, buds respond by producing new shoots (Miller 2000) and this engenders a rapid return to pre-fire conditions (Fig. 9.1). Many studies have described vegetation response in areas where sprouting species dominate, concluding that regeneration following fire is similar to an autosuccessional process that compensates for the regression (Tárrega and Luis-Calabuig 1989; Naveh 1990; Trabaud 1990, 1998, 2002; Vera de la Fuente 1994; Badía et al. 1995). Post-fire sprouting by belowground survivors is successful and the fire may even have a stimulating effect on sprouting vigour (Buhk et al. 2007).

**Fig. 9.1** Fire recurrence in resprouter (*Quercus coccifera*) scrubland in the Aragonese Pre-Pyrenees (Spain, August 2001): vegetation regeneration after fire in 1991

In Mediterranean-type ecosystems, seedling establishment may originate from on-site seeds (soil seed banks and/or serotinous cones) or from off-site seed sources. In the case of on-site seeds, high temperatures can break hard seed coat dormancy, making seed banks ready to germinate if favourable environmental conditions appear following fire (Baeza and Roy 2008). In Mediterranean-type ecosystems, serotinous trees such as *Pinus halepensis*, *Pinus pinaster* exhibit powerful mechanisms of fire-induced seed germination (Trabaud 1987; Barbéro et al. 1998). Serotinous species are characterized by the long-term retention of seeds within mature closed cones which, when heated by fire, open to release seeds onto the soil. The cone opening process requires melting the resins that bind the apophyses of the cone scale (Schoennagel et al. 2003). In addition, *Pinus halepensis* seedlings are highly tolerant to hydric stress (Zavala et al. 2000) and this allows them to resist the harsh environmental conditions of burned areas, with high temperatures and bare soil that favour water loss.

Mass liberation of seeds after wildfire can lead to a successful, natural regeneration of Aleppo pines and their continued dominance in the community (Fig. 9.2). However, on a regional scale, post-fire regeneration of Aleppo pines AQ1 may vary (Pausas et al. 2004); many other factors affect post-fire seed germination: the presence and quality of a canopy seed bank, competition from understory pine forests, the amount of pre-fire pine biomass, geo-physical conditions, the distance to the unburned forest and the severity of the fire (one of the most important factors controlling post-fire dynamics – vegetation succession and post-fire hydrological processes).

**Fig. 9.2** *Pinus halepensis* forest regeneration in Sierra de Luna (Ebro Valley, Zaragoza, Spain, June 2006) one year after the fire

Finally, there are some species (*Bupleurum rigidum*, *Thymus vulgaris* etc.) that may involve vegetative and sexual reproduction after fire. These are often known as facultative resprouters (Naveh 1975; Buhk et al. 2007).

## 9.2.2 Environmental Conditions

As already mentioned, there are many environmental factors that condition vegetation response to fire. A number of papers and studies have dealt with the issues but there is some confusion concerning permanent and non-permanent factors. Factors influencing vegetation recovery can be classified as structural factors, that do not change with fire irruption (topographic conditions, bedrock, vegetation types) and temporary factors, which are the specific post-fire conditions of a site (fire severity, the season, post-fire precipitation, management practices etc.).

According to Key and Benson (2005), fire severity is the direct effect of the combustion process. Generally speaking, high-severity burnt areas register higher-rates of soil loss (McNabb and Swanson 1990) and lower-rates of vegetation recovery, due to the higher consumption of the forest floor, shallow buried seeds and the destruction of canopy (Robichaud and Waldrop 1994; DeBano et al. 1998). In contrast, a rapid return to pre-fire conditions can be expected if the fire burned at low severity. Severe fire is a significant factor affecting landscape patterns of post-fire forest recovery because of its influence on seed germination and resprouting activity. High

temperatures can affect seed viability (Salvador and Lloret 1995) and can induce significantly higher mortality in resprouter plant species caused by the destruction of meristematic tissues, as observed by Lloret and López-Soria (1993) in the evergreen Mediterranean shrub *Erica multiflora*. In southeast Spain, Pausas et al. (2003) found better regeneration of *Pinus halepensis* forests at high fire severity sites as a consequence of the increased post-fire nutrient concentration.

Whilst the rate of germination may be enhanced by the heat from fire, the germination of some plant species, such as *Pinus Pinaster*, can decrease, when seeds are subjected to temperatures higher than 130–200°C (Torres et al. 2006; Vega et al. 2008).

With the germination of non-serotinous species, distance to unburned forest can be another important factor. Gracia et al. (2002) carried out a long-term study (37 years after the fire) of factors affecting successional dynamics of a mixed pine-oak forest and they concluded that distance to the unburned forest was the main factor affecting current pine density; the explanation is that non-serotinous pine depend on external seed sources. In contrast, oak density did not vary with distance, thus illustrating the fact that the main restriction for resprouters is their inability to disperse over long distances (Buhk et al. 2007).

In resprouting plant species, carbohydrate storage has been suggested as an important mechanism by which plant size influences the resprouting response in *Quercus coccifera* (Trabaud 1991), though not all species have been considered (Pausas et al. 2003).

Another important factor in the recovery processes is the season in which the fire takes place, as this affects resprouting ability and vigour; Allen and Partridge (1988) argue that greatest damage is caused by fires at the end of summer or at the beginning of autumn.

With regards to topographic variables, Gracia et al. (2002) found notable aspect differences due to differences in water stress. Water stress is the principal factor limiting the distribution and growth of species in Mediterranean regions (Mooney 1983; Zavala et al. 2000).

Konstantinidis et al. (2006) monitored the resprouting dynamics of *Arbutus unedo* and concluded that aspect has an important effect on both the height and diameter of resprouts. Pérez-Cabello (2002) also determined that aspect plays a significant role on spatial distribution of density 15 years after fire. Gracia and Retana (2004) analysed variance in the sprouting ability of the Holm oak and found that position on the slope is a key factor in size differentiation – a lower-position indicates more favourable conditions.

## 9.3 Changes in Mediterranean Soils Affected by Fire

The impact of fire on soil properties has generated much research interest in the last twenty years (Shakesby and Doerr 2006). Fire-affected soil can suffer direct physical and chemical alterations as a consequence of the increased temperatures

and the incorporation of the charcoal-ash (Giovannini 1994; Giovannini et al. 1998) and there are also indirect changes that result from the new situation created by the loss of vegetation cover and increased susceptibility to water and wind erosion (Mataix-Solera 1999). These changes depend, to a large extent, on the severity of the fire, "severity" being understood as the intensity of the temperature and the duration of the fire, even though it is quite difficult to quantify these parameters under natural conditions.

In general, soil physical characteristics deteriorate post-fire whilst chemical characteristics improve (with variable time-scale) (Díaz-Fierros et al. 1994; Martínez-Fernández and Díaz-Pereira 1994).

Blackened soil without vegetation cover results in an increase in temperature and reduced water retention and absorption. However, despite the fact that flame temperatures can reach more than 1,400° (DeBano et al. 1998), maximum soil temperatures are between 500–800° and fall significantly in line with soil depth and the temporal delay conditioned by soil humidity (Dimitrakopoulos and Martin 1994); this means that the highest temperature reached by a fire only affects the first few centimetres of soil. Úbeda (1998), studying the burned sector of a mountain on the Catalan littoral (NE Spain) found that the surface temperature had reached 600° but at a depth of 1 cm it was 50°. Several authors (Giovannini 1994; Pardini et al. 2004) assert that soil temperatures of under 220° do not significantly alter the characteristics of the soil. Temperatures of between 220 and 460° cause the combustion of some cohesive agents and other organic substances of the soil. Temperatures that are above 460° for enough time can cause total combustion of organic material and carbonate decomposition.

The most important soil parameters affected by fire are soil pH, the quantity of nutrients and organic material, the establishment of aggregates, porosity and hydrophobicity. Changes in these parameters are reflected in the hydrogeomorphological behaviour of the soil.

The pH of fire-affected soil tends to increase as the charcoal-ash adds carbonates, oxides and base cations (Ulery et al. 1993). This can favour micro-organism activity but it can also generate problems of vegetation nutrition, as described by Mataix-Solera and Guerrero (2007) in a study in Valencia. Another consequence of the charcoal-ash is an increase in electrical conductivity and salinity, a phenomenon observed in the semi-arid soils of the Ebro Valley in north-east Spain (Badía and Martí 2003) and pine plantations in Israel (Kutiel and Inbar 1993).

The combustion of vegetation and leaf litter frees nutrients. Some of the nitrogen volatilises, while the phosphorus, magnesium, calcium and potassium may be returned to the soil in the form of ashes. This is why there is often a temporary, post-fire increase in fertility that can encourage the regeneration of the vegetation and organic material. However, the post-fire growth in nutrients may quickly fall if overland flow and lixiviation increase in steep gradient locations or with heavy rain which may result in greater soil erosion (Andreu et al. 1994). In general, in the post-fire period, there is an increase in assimilable phosphorus and a decrease in soluble phosphorus; there is a loss in total nitrogen depending on the intensity and

temperature of the fire Sánchez et al. (1994), but there is a rise in inorganic nitrogen which results in a temporal upsurge in fertility (Rashid 1987).

The amount of organic carbon is linked to the intensity of the fire – in low-intensity fires, organic carbon can increase due to partially burned vegetation. However, if the fire is high-intensity, carbon levels may be reduced, both in more humid forest conditions (Bará and Vega 1983) and Mediterranean forests (Mataix-Solera et al. 2002). The raised level of organic material and the stability of aggregates in the immediate aftermath of the fire can be reversed after the first post-fire rains which can cause erosion of the charcoal-ash and surface soil horizons (Campo et al. 2008). These alterations are particularly significant in the arid or semi-arid Mediterranean soils with low organic material content and less resilience (Giovannini et al. 1990).

The heat consumes part of the organic material and can alter the stability of soil aggregates (Giovannini et al. 1990; Kutiel and Inbar 1993; DeBano 2000; Andreu et al. 2001; Mataix-Solera et al. 2002), a key parameter in post-fire, soil resistance to erosion. The most important agents that control aggregates are the amount of organic material, calcium carbonate, organic-mineral components and microbial activity (Le Bissonnais 1996; Boix-Fayos et al. 2001). Aggregate stability response to fire is complex; it may rise in cases of low-intensity fire (Úbeda 1998, 2001; Úbeda and Bernia, 2005), through the aggregation of argillaceous components and sand particles (Giovannini 1994), in situations of aggregate selection produced by post-fire rains that carry away those of least resistance, or due to the presence of hydrophobic substances that act as cementers (Mataix-Solera and Doerr 2004; Arcenegui et al. 2008a, b). Aggregation levels have also been observed to fall (Cerdà 1993; Badía and Martí 2003) in high-intensity fires that cause a reduction of organic material.

In bare, blackened soil, porosity can diminish as the fine particles are spread by the splashing of the post-fire rain and fill soil pores, thereby reducing water infiltration and increasing surface runoff. The splash is particularly strong in the intense Mediterranean rains and can even lead to surface scaling which increases channelling and runoff. Soils show a high vulnerability to raindrop impact and the rainfall causes significant changes in some soil properties due to the development of a thin and friable surface crust (Llovet et al. 2008a).

Furthermore, fire vaporises organic matter that condenses where the soil temperature is lower and this can generate a water repellent layer (hydrophobicity) which is especially active in sandy and acidic soils. Water repellence, studied since the 1960s (DeBano 1971), increases with the accumulation of charcoal-ash, the volatilisation of organic compounds and their condensation around the soil aggregates. The process is also related to the severity of the fire (Doerr et al. 2006) and factors such as the thickness of the organic horizon, hydraulic conductivity, prior humidity and porosity (Leighton-Boyce et al. 2007). Nevertheless hydrophobicity may augment or be destroyed, depending on the temperature of the fire and the characteristics of the affected soil, particularly in terms of soil organic matter and clay. Josa et al. (1994) described the role of fire temperature and its relationship with hydrophobicity in a study of a Mediterranean oak forest; hydrophobicity reached maximum values at 200° but disappeared at 300°.

## 9.4 Hydro-Geomorphic Alterations in Fire-Affected Mediterranean Soils

In the short-term, forest fires eliminate vegetation cover and modify it in the long-term, accelerating soil losses from Mediterranean ecosystems. The transformations produced by fire must be considered in a bioclimatic context of Mediterranean characteristics with environmental conditions that clearly favour soil degradation. The impact of fire on the soil cannot be analysed without taking into account this environmental context (Martínez-Fernández and Díaz-Pereira 1994).

The increase in hydrological and geomorphological activity following wildfire tends to occur during the "window" of disturbance (Prosser and Williams 1998) that can vary in duration from one month to many months (Shakesby and Doerr 2006).

The intensity of the fire is one of the fundamental factors that condition the magnitude of the hydro-geomorphic changes and the post-fire vegetation regeneration (Gimeno et al. 2000). Lucchesi et al. (1994) analysed vegetation regeneration after two fires of contrasting intensity and found that low-intensity fire promotes rapid sprouting and recovering. Fire frequency is also a key element in processes of environmental degradation and even desertification in fragile environments such as the Mediterranean scrublands.

One of the most noticeable effects related to fire temperature is mechanical weathering of the rocky substrata and the consequent production of ignifracts caused by spalling (Ballais and Bosc 1992) in particular, favourable lithologies that are broken and flaked (Fig. 9.3).

Vegetation covering, especially forest covering, increases environmental humidity, reduces evaporation and facilitates soil water infiltration. Vegetation also determines the generation of runoff and controls rates of infiltration (Cerdà 1995b). Infiltration is partly related to soil depth (Mataix-Solera and Guerrero 2007) and when infiltration capacity is reduced the proportion of runoff is raised and this augments the effects of erosion (Llovet et al. 1994). In post-fire conditions, rates of runoff and infiltration are fundamentally regulated by vegetation regeneration (Cerdà 1998; Pérez-Cabello et al. 2000). Cerdà and Doerr (2005), using a rain simulator in a Mediterranean pine forest, observed that three years after the fire, vegetation regeneration reduced surface runoff by 18% compared to the measurement on bare soil, six months after the fire.

In the process of vegetation alteration, burned vegetation can play an important role in the interception of rainwater, the activation of cortical runoff, the higher levels of water entering the soil and the reduction on the splash effect (Pérez-Cabello et al. 2000, 2002) which can provoke a diminution of overland flow and soil loss. Added to this, post-fire leaf litter can lead to the development of small dams that trap sediment on low-gradient hillsides (Díaz-Fierros et al. 1994), increasing water storage capacity when the leaf litter mixes with the charcoal-ash (Cerdà and Doerr 2008).

**Fig. 9.3** Weathering of Miocene sandstones, caused by a wildfire in August, 2008 (Montes de Zuera, Zaragoza, Spain)

The post-fire presence of a blanket of charcoal-ash can regulate hydro-geomorphic soil behaviour which avoids erosion in the immediate aftermath of the fire by absorbing initial precipitation (Cerdà 1998; Pannkuk and Robichaud 2003; Leighton-Boyce et al. 2007). Nevertheless, this protection is short-lasting and over time is washed away by overland flow and the soil is left uncovered and subject to the erosion process.

Another physical parameter that is altered by fire and has hydro-geomorphic consequences is porosity. As previously mentioned, fine particles generated by the splashing of the heavy and frequent post-fire rains fill soil pores, reducing aeration and infiltration capacity.

One of the most common post-fire alterations concerns soil self-humidification capacity. Fire can induce hydrophobicity in non-repellent soils and strengthen or weaken pre-existing surface repellence, depending on the amount and type of organic horizon consumed and the temperature of the fire (Doerr et al. 1996, 2004).

In cases where fire has resulted in greater hydrophobicity, infiltration is reduced and surface runoff increases (Úbeda et al. 1990; Imeson et al. 1992) and this diminishes soil humidity (Úbeda et al. 2002). Leighton Boyce (2002), in study in Portugal, showed that hydrophobicity increased by 26 times, in comparison with non-water repellent soils.

Whilst it is true that acidic and sandy soils are more susceptible to hydrophobicity, recent studies in calcareous Mediterranean soils have also revealed levels of hydrophobicity (Cerdà and Doerr 2007; Mataix-Solera et al. 2007; Arcenegui et al. 2008a, b).

Another environmental factor that conditions post-fire hydro-geomorphic behavior is topographic exposition. In south-facing hillsides post-fire erosion is of greater intensity in shaded areas (Llovet and Ponce 1996; Pérez-Cabello et al. 2000, 2002) with more abundant biomass, where fires reach higher temperatures and are of longer duration (Ruiz-Gallardo 2004). Post-fire environmental conditions are more precarious in south aspect hillsides so erosion levels tend to be higher (Marqués and Mora 1992; Andreu et al. 2001). Vegetation regeneration is more accelerated on shaded hillsides, quickly stabilising erosion values and soil loss (Pérez-Cabello et al. 2002) (Fig. 9.4).

Finally, the use of the soil is a relevant factor in relation to fire. Hillside terracing for farming and its abandonment in the 1960s has led to a process of the establishment of scrubland and posterior colonisation by arboreal species common to Mediterranean ecosystems. In these environments, fire alters the hydro-geomorphic behaviour, reducing hydro-infiltration and fostering the production of sediment on the scale of the terrace, in comparison with the scale of the basin (Llovet et al. 2008b).

Forest fires result in a general fall in infiltration rates and an increase in overland flow and soil water erosion, which leads to the appearance of other erosion forms. Where soils contain stones and/or substantial roots, stone or root capped pedestals may develop by sheet wash and the appearance of rills and gullies. Where water does become concentrated, it can form extensive rill systems, particularly on steep slopes (Shakesby and Doerr 2006) (Fig. 9.5), and even activate mass movements in specific, favourable conditions such as hillside terracing.

**Fig. 9.4** Low-intensity fire and vegetation regeneration by *Brachypodium pinnatum* and *Helictotrichon cantabricum*, nine months after fire in a north aspect slope in a sub-Mediterranean forest (Huesca, Spain)

**Fig. 9.5** Rills following a fire in August, 2008 (Zaragoza, Spain)

Techniques for post-fire erosion measurement are employed with a variety of time-space scales, from the application of the USLE (Universal Soil Loss Equation) to erosion picks (Pérez-Cabello et al. 2006b). The most widely used tool is open and closed erosion parcels, which identify soil losses immediately after high intensity fires (up to 4 magnitude orders in Úbeda and Sala 1996), that are rapidly reduced after the regeneration of vegetation cover and can reach values that are even inferior to the pre-fire situation due to sediment exhaustion (Cerdà and Lasanta 2005).

Hydrological responses to fire at the catchment scale have received less attention than higher scales, largely because of the greater difficulties of installing and maintaining instruments, the long recovery period or the greater spatial heterogeneity of environmental factors such as geology, topography, vegetation and soils, as well as fire extent over large catchments, fire severity and fire history. The quantification of the flow and sediment in basins confirms a higher presence of growth peaks after the fire (Belillas 1994; Martín and Chevalier 1994; Echeverría et al. 2005) and an increase in sediment production (Mayor et al. 2007). The most likely cause of the peak is Hortonian overland flow enhanced by litter destruction lowering the surface storage capacity of rainfall and reducing surface roughness, together with the water-repellent nature of the soil in some forests. López and Batalla (2001), in a post-fire study in Catalonia, noted an increase of 30% in sediment production and 120% in flow growth peaks.

Finally, one of the most utilised tools for measurement of post-fire sediment production and flow is rain simulation, a method that is particularly apposite for the time-space variations of the Mediterranean environment. Rain simulations have confirmed that soil losses sharply increase in the post-fire period, especially in

October, when the soil is bare (Cerdà et al. 1995) and the first rains are the key to the scaling and blocking of pores by the ash (Llovet et al. 1994).

In any case, at the patch scale, fire has great impact on runoff production, but at the slope scale, runoff is not seriously affected by fire unless there is another kind of disturbance (Pradas et al. 1994). Soil losses per unit are negatively related to the scale and translate to large scale sediment storage (Shakesby and Doerr 2006). It seems that post-fire loss of soil rates are not more than 1 Mgha$^{-1}$año$^{-1}$, a rate that can be considered as acceptable (Cerdà and Bodí 2007). More precise measurements in recent years indicate that fires increase soil losses during the first year but in a few years (2–8), values return to pre-fire levels (Cerdà and Bodí 2007). The greatest damage is produced in areas that suffer a long dry season which can affect the mineral horizon (Pausas and Vallejo 1999).

The highest rates of erosion in burned surfaces are probably registered in paths and lines cut for the transport of cut wood (Úbeda and Sala 1996; Pérez-Cabello et al. 2003) and firebreaks (Cerdà 1995a) (Fig. 9.6). This fact is of particular relevance when deciding on treatment of burned areas.

Post-fire forest management activities must be based on the analysis of the physical, chemical and biological impact of the fire on the soil in the short, medium and long-term. There should also be extensive research on the hydro-geomorphic changes and their effect on erosion.

Techniques for post-fire reforestation can activate soil loss. Post-fire management manuals and good practices guides are therefore required. The preparation of Expert Systems for the integrated fight against forest fires on a regional and local scale are also necessary and the use of Geographic Information Systems and spatial Teledetection for identification and multi-temporal monitoring of burned spaces is also recommended (Pérez-Cabello et al. 2008).

## 9.5 The Role of Remote Sensing Methods on Fire Effects

There is widespread interest in mapping and predicting regional environmental processes, such as erosion, by means of predictive models (de Jong et al. 1999). Remote sensing data and methodology play an important role in the detection, description and analysis of the consequences of wildfires in the medium and long-term. Multispectral satellite data has become a common aid in the identification of changes to ecosystems (Miller and Thode 2007) and a support for post-fire management. Optical imagery from earth observation satellites enables managers to identify burned areas and locales in need of special management to reduce degradation processes (Lentile et al. 2006) and for studying the regeneration of plant communities in the long-term (Röder et al. 2008; Vicente-Serrano et al. 2008).

### *9.5.1 Monitoring Temporal Patterns of Vegetation Recovery*

The impact of fire and the subsequent recovery process may be identified and monitored by means of remote sensing (Patterson and Yool 1998; Bobbe et al.

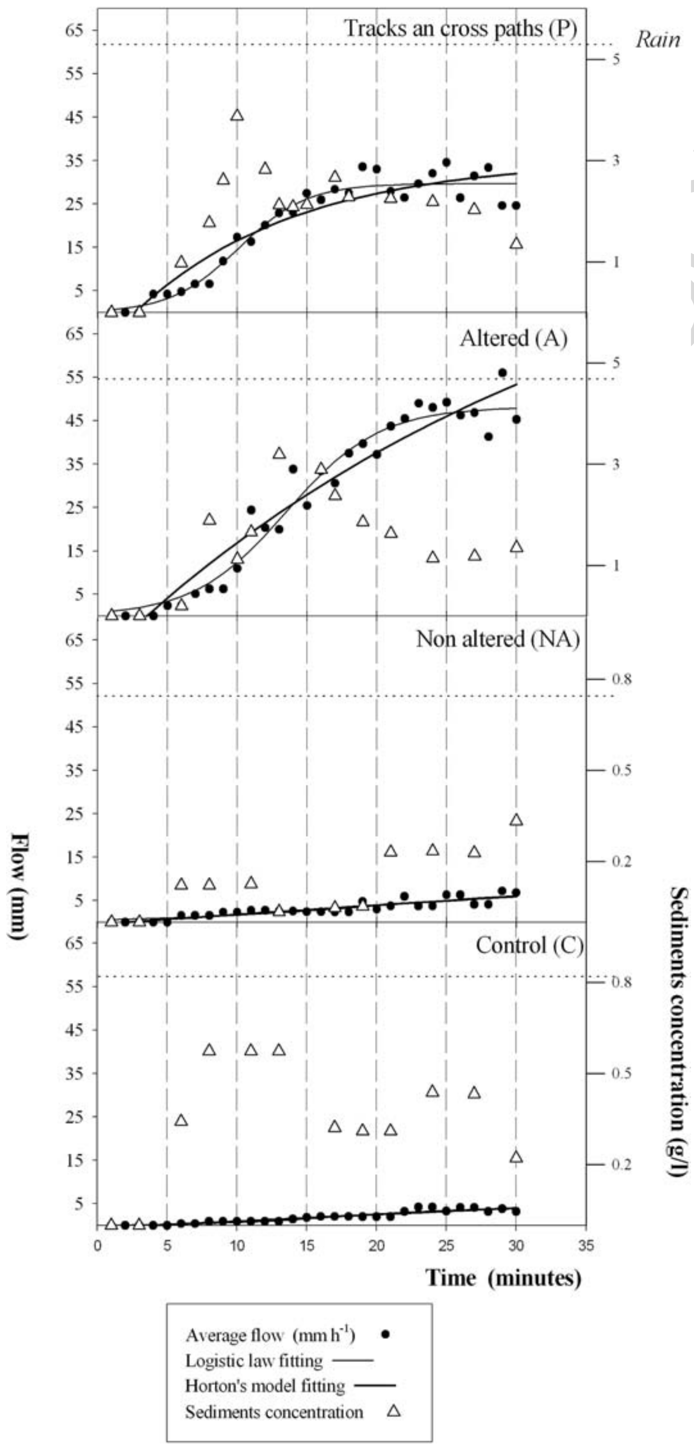


**Fig. 9.6** Average rate of flow observed in different test areas of a fire in the Pre-Pyrennees (Spain) (after Pérez-Cabello et al. 2003)

2001; Rogan and Franklin 2001; Escuin et al. 2002; Van Wagtendonk et al. 2004).

Remote sensing data is particularly apposite for monitoring post-fire processes on a regional scale for two reasons: (i) its sensibility to alterations in the radiometric response to wildfire-induced changes and the increase of the vegetation cover; (ii) the spatial and temporal resolution of satellite imagery allows the characterization of the time of response patterns.

Changes in reflectance values caused by the disappearance of charcoal-ash remains, the increase of vegetation cover and the subsequent decrease of bare soil caused by the recovery process are targets for remote sensing. Increases in infrared reflectance and consequent decreases in red and blue wavelengths (caused by increases in chlorophyll) are registered. Satellite imagery cover large areas and the temporal recurrence of the data collection facilitates analysis of the regeneration process. A number of studies evidence the potential of remote sensing data for increasing our knowledge of the post-fire dynamic. Examples of remote sensing fire recovery research in Mediterranean ecosystems include: Jakubauskas et al. (1990), Marchetti et al. (1995), Steyaert et al. (1997), Viedma et al. (1997), Henry and Hope (1998), Ricotta et al. (1998), Díaz-Delgado and Pons (2001), Pérez-Cabello (2002) and Thompson et al. (2007). Furthermore, the use of remote sensing data permits measurement of forest regeneration rates (White et al. 1996; Viedma et al. 1997; Epting and Verbyla 2005), the analysis of the role of topographic and geographic factors on vegetation recovery (Viedma et al. 2006; Wittenberg et al. 2007) and the investigation of resilience and forest decline processes related to burn severity and recurrent fires (Díaz-Delgado et al. 2002; Thompson et al. 2007). The Normalized Different Vegetation Index (NDVI) (Rouse et al. 1973) has been the most frequently used tool for monitoring, analyzing, and mapping temporal and spatial post-fire variations (Viedma et al. 1997; Díaz-Delgado et al. 2002, 2003) (Fig. 9.7). Other techniques employed are: Principal Components Analysis (Fung and LeDrew 1987); Kauth-Thomas Transformation (Crist and Cicone 1984); Spectral Mixture Analysis and Spectral Vegetation Indices (Townshend and Justice 1986; Röder et al. 2008).

The most important connection between Landscape Ecology and Remote Sensing is based on the importance of vegetation on the landscape structure and the huge potential of remote sensing for analyzing vegetation cover characteristics (composition and spatial distribution). From the point of view of physiognomic diversity, spectral and temporal resolution of remote sensing products offers an ideal perspective for assessing the effects of wildfire on the landscape, on a regional scale (Chuvieco et al. 1999). Some authors argue that following fire, there is an increase in homogeneity (Chuvieco, 1996) as a consequence of the destruction of vegetation. Lloret et al. (2002) observed an increase of patch density and a decrease of patch size in burned areas due to different post-fire vegetation succession phases coexisting in the same area. Pérez-Cabello et al. (2005) found a high increase in diversity values caused by the different vegetation responses of plant communities, of charred and burnt vegetation remains and post-fire charcoal-ash. The increase in diversity values following a fire is inversely proportionate to pre-fire diversity values. On the

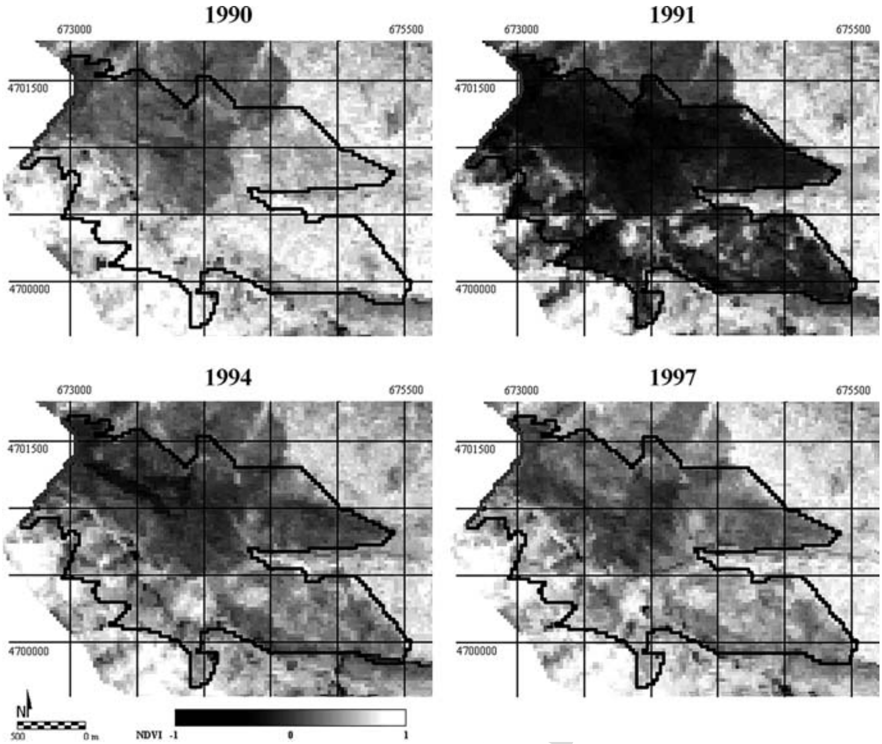


**Fig. 9.7** Nofuentes forest fire (21st August, 1991, Pre-Pyrennees, Spain) NDVI evolution: pre-fire, 1990; post-fire, 1991, 1994, 1997 (after Pérez-Cabello and de la Riva 2003)

other hand, if, 7-years after the fire, the different plant communities show similar values, it means that there is no statistically significant difference among plant communities and it can be said that, on a global scale, fire leads to an increase in homogenization.

### *9.5.2 Mapping Erosion-Sensitive Areas*

The use of remote sensed data, in combination with Geographical Information Systems (GIS) and digital elevation models (DEM) has been applied to mapping erosion (Bocco 1991; Martínez-Casasnovas and Poch 1998; Pérez-Cabello 2002) and for collecting information regarding runoff and erosion models (de Jong et al. 1999; King et al. 2005). An overview of methodologies applied to mapping soil erosion by means of satellite remote sensing was published by Vrieling (2006).

Remote sensed data has been used in different ways: (i) for detection of erosion features, (ii) for assessment of eroded areas (iii) for controlling factor mapping. The reduced spatial extension of many erosion features often hinders the use

satellite imagery, so many of the parameters influencing infiltration and runoff (soil surface roughness, soil porosity, soil texture, and initial moisture content) are not directly detected by satellite (King et al. 2005). Better results have been obtained for assessing eroded areas and, in particular, for mapping factors controlling the spatial distribution of soil erosion. Soil and vegetation attributes have been most widely determined by means of satellite data, especially using optical satellite systems, with Landsat being most commonly used because of the length of its time series (Vrieling 2006). With regards to burned areas, in the last decade, one of the most significant advances has been the incorporation of fire characteristics through severity indexes and, as Vafeidis et al. (2007) indicate, remote sensing is the only practical and cost-effective method for mapping burn severity.

Although the potential of the joint use of remote sensing and GIS in modelling post-fire hazards has not been fully realized (Vafeidis et al. 2007), proposals have been developed for mapping erosion-sensitive areas: Pérez-Cabello (2002) employed different structural criteria including topographical parameters, climatological conditions etc. to map erosion-sensitive areas, emphasizing the role of burned vegetation remains using Landsat imagery; Ruiz-Gallardo et al. (2004) applied Normalized Difference Vegetation Index (NDVI) methodology to highlight post-fire management requirements related to the identification of potential erosion areas; Fernández et al. (2005) generated a susceptibility model for post-fire soil erosion by means of mapping fire intensity; Perez-Cabello et al. (2006a) estimated the probability of high erosion in order to map erosion-sensitive areas after fire, in the Pre-Pyrenean area (Spain). Three-year Landsat Thematic Mapper (TM) images, physical variables incorporated into a GIS and different logistic regression (LR) models were used for mapping the probability of erosion. The authors concluded that pre-fire Normalized Difference Vegetation Index (NDVI) values and aspect are the most important variables for estimating erosion-sensitive areas after fire; Vafeidis et al. (2007) proposed a method that integrates GIS, remote sensing and digital cartographic data, for the quantitative estimation and mapping of post-fire-erosion and runoff. The method is based on the Thornes (1985) soil-erosion model that takes into account fire temperature, using AVHRR and ATSR images.

Miller et al. (2003) used a GIS-based implementation of the Revised Universal Soil Loss Equation (RUSLE) to model soil erosion. They used Landsat images for estimating the pre-fire cover factor and to map canopy consumption. An important contribution was their description of the effects of burning on soil hydrophobicity and spatial variability on adjusting the soil erodibility factor ($k$) according to burn severity. Fox et al. (2008) used multi-temporal SPOT images for mapping burn severity and post-fire soil erosion risk mapping.

Other spatially distributed models for assessing fire impact on erosion and for identifying vulnerable areas prone to runoff increase are HEM-GIS (Wilson et al. 2001) and SPLASH (Beeson et al. 2001). The former is an analytical hillslope erosion model integrated into a GIS framework while the latter simulates overland flow using Manning's equation on a landscape-scale. Finally, in the USA, fire effects mapping has become standard practice for post-fire resources management (Miller and Yool 2002). Teams and researchers from the interagency Burned Area

Emergency Rehabilitation (BAER) have developed methodologies for minimizing the effects of post-fire erosion.

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# Chapter 9

| Q. No. | Query |
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| AQ2 | Au: Please specify whether "Bobbe et al. 2001" is "2001a" or "2001b". |
| AQ3 | AU: Please specify whether “Chuvieco, 1999” is “1999a” or “1999b”. |
| AQ4 | Au: "Pérez-Cabello et al. (2005" is not listed in the reference list. Please provide. |

# Chapter 10
# Remote Sensing of Burn Severity

**Ioannis Z. Gitas, Angela de Santis, and George H. Mitri**

## 10.1 Introduction

When a forested area is damaged by fire, detailed and current information concerning the location and extent of the burned area, as well as the immediate effect of fire on the environment, is important to assess economic losses and ecological effects, monitor land use and land cover changes, and model atmospheric and climatic impacts of biomass burning (Pereira et al. 1997). More specifically, accurate information relating to the impact of fire on the environment and the way it is distributed throughout the burned area is a key factor in quantifying the impact of fires on landscapes (van Wagtendonk et al. 2004), selecting and prioritizing treatments applied on site (Patterson and Yool 1998; Bobbe et al. 2001), planning and monitoring restoration and recovery activities (Jakubauskas 1988; Jakubauskas et al. 1990; Gitas 1999) and, finally, providing baseline information for future monitoring (Brewer et al. 2005).

Two terms, namely fire severity and burn severity are currently used to describe the evident effects of fire on the ecosystem. From the two terms, fire severity has been used for a longer period of time in the literature (Ryan and Noste 1985; Turner et al. 1994; Chappell and Agee 1996; White et al. 1996; Wang 2002; Brewer et al. 2005; Doerr et al. 2006; Mitri and Gitas 2008), while burn severity has been introduced more recently (Patterson and Yool 1998; van Wagtendonk et al. 2004; Chuvieco et al. 2005; Key and Benson 2005; Chuvieco et al. 2006, 2007; De Santis and Chuvieco 2007, De Santis and Chuvieco 2009; De Santis et al. 2009). Although in most cases fire severity and burn severity are used interchangeably to describe the evident effects of fire on the ecosystem in terms of biophysical alteration (e.g. crown scorch, soil exposure, depth of burn, fuel consumption), there have been a number of cases (Lentile et al. 2006; Kasischke et al. 2008; French et al. 2008) in which fire severity is defined as a measure of the immediate fire impact on the environment,

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while burn severity as a measure of the way in which the ecosystem recovers after a fire. It should be noted that Key (2006) further differentiates burn severity as:

Short-term, which is related to the initial assessment of the impact of fire, and long-term, which is related to the extended assessment of the impact of fire.

Burn severity can often be characterized by the intensity and residence time of the fire. Intensity and residence time within a fire area are dictated by a host of environmental factors such as weather conditions, slope, prefire vegetation condition and type, and ladder fuels. For example, some areas burn at a very hot temperature for long periods of time, destroying virtually all vegetation in the area and causing extensive damage to the soil. Other areas may have been subjected to fire for only a short period of time, killing the undergrowth and then advancing (Clark and Bobbe 2006). Burn severity is defined here (from a landscape perspective) as the degree of environmental change caused by fire as a part of the initial assessment.

Traditional methods of recording burn severity include field work or observations from an airborne platform, followed by the mapping (manually) of resource damage into predetermined classes. As fire sizes increase and time becomes a constraining factor, traditional methods have become costly and labour-intensive to the point where accurate mapping of severity classifications is precluded (Bertolette and Spotskey 2001; Mitri and Gitas 2008). Given the extremely broad spatial expanse and often limited accessibility of the areas affected by fire, satellite remote sensing is an essential technology for gathering post-fire related information shortly after the fire event in a cost-effective and time-saving manner (Smith and Woodgate 1985; Chuvieco and Congalton 1988; Jakubauskas et al. 1990; White et al. 1996; Patterson and Yool 1998; Beaty and Taylor 2001; Escuin et al. 2002).

The removal of vegetation, the exposure of soil, and changes in soil and vegetation moisture content as a result of differences in burn severity imply changes in reflectance (Jakubauskas et al. 1990; White et al. 1996) which make remote sensing a good alternative when mapping the immediate effects of fire to the environment. Since the initiation of the Landsat satellite program (1972), several projects have been conducted to test the potential efficiency and reliability of satellite data in collecting information for forest fire management. However, it is only during the last decade that the range of applications has increased significantly. As a result, different types of satellite imagery and image analysis techniques have been employed in a number of studies. However, despite the increase in the number of publications in recent years, the accurate mapping of burn severity remains an active topic of research.

The aim of this chapter is to review the role of Remote Sensing (RS) in estimating burn severity. More specifically, methods and techniques that have so far been employed to estimate burn severity on the ground and by RS will be reviewed and future trends in estimating burn severity will be identified.

## 10.2 Field Estimation of Burn Severity

The methods conventionally employed to produce severity maps are based on extensive field visits to the burned area and the mapping of resource damage into

**Table 10.1** Field variables assessed to determine burn severity (after De Santis and Chuvieco 2009)

| Variables assessed in the field | Reference |
|---|---|
| Percentage of tree basal area mortality | Chappell and Agee (1996) |
| Decrease in plant cover | Jain and Graham (2004); Rogan and Yool (2001) |
| Volatilization or transformation of soil components into soluble mineral forms | Turner et al. (1994); Wang (2002); Wells and Campbell (1979) |
| Proportion of fine branches remaining on the canopy | Moreno and Oechel (1989) |
| Degree of canopy consumption and mortality | Ryan and Noste (1985); Kushla and Ripple (1998); Patterson and Yool (1998); Rogan and Franklin (2001); Doerr et al. (2006); Kokaly et al. (2007) |
| Char and ash cover | Smith et al. (2005) |
| Composite Burn Index (CBI, Key and Benson 2005) and its modifications | Miller and Yool (2002); van Wagtendonk et al. (2004); Cocke et al. (2005); Epting and Verbyla (2005); Key and Benson (2005); Sorbel and Allen (2005); Wimberly and Reilly (2006); Chuvieco et al. (2007); De Santis and Chuvieco (2007); Miller and Thode (2007). |

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predetermined classes (Bertolette and Spotskey 2001). Field estimation of burn severity is based on visual observations of the effects of fire on vegetation and soil, as well as on the assessment of a number of related parameters (Table 10.1) such as the condition and color of the soil, the amount of fuel consumed, the resprouting of burned plants, the blackening or scorching of tree-leaves, the depth of burn in the soil, and changes in fuel moisture (Roy et al. 2006; De Santis and Chuvieco 2009).

Burn severity maps are more dependent on robust field validation (White et al. 1996) than maps of fire presence/absence (Hudak and Brocket 2002) so in order to facilitate the objective collection of data on the ground a number of field protocols as well as burn severity coding matrices annexed to these protocols have been developed. Most of these coding matrices are based on severity ratings of individual strata related to soil and vegetation, and include simple classes such as unburned, low, moderate, and high severity.

In order to quantify the fire effects and ensure consistent and comparable estimations of burn severity across broad geographic regions, the use of a common index to be measured was recently proposed (Key and Benson 2002b, 2005; Key 2006). As a result, the Composite Burn Index (CBI) was developed by Key and Benson (2002a, 2005) within the framework of the FIREMON[1] (Fire Effects Monitoring and

[1] In 2008, FIREMON has been integrated with the NPS Fire Ecology Assessment Tool into a new monitoring tool called FFI (FEAT/FIREMON Integrated).

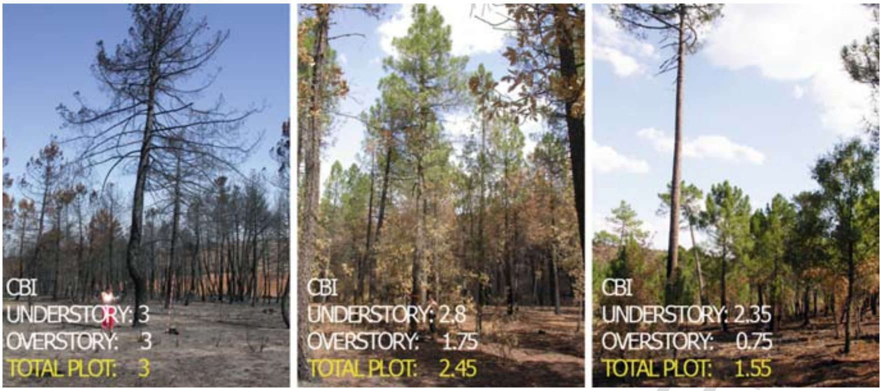


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**Fig. 10.1** Examples of high, moderate and low burn severity values observed in the field*

Inventory Protocol) project. The CBI, which entails relatively large plots, is based on independent severity ratings for individual strata (substrate, herbs/low shrubs, tall shrubs/saplings, understory trees, and canopy trees) and synoptic scores (ranging from 0: non-burned to 3: completely burned) for the whole plot area (Fig. 10.1).

Plot sampling for the estimation of CBI may be implemented in a stand-alone field survey for individual site assessment or may serve to calibrate and validate remote sensing results, i.e. to relate detected radiometric change with actual burn characteristics on the ground. In the second case the CBI is usually used complimentary to the Normalized Burn Ratio (NBR), which is derived from remotely sensed data. NBR is computed as the difference between near-infrared (NIR) and middle-infrared (MIR) reflectance divided by their sum. The NBR is temporally differentiated between pre- and post-fire datasets (dNBR) to determine the extent and degree of detected change (Key and Benson 2005; Key and Benson 2002a; Lutes et al. 2006). Although the results of the correlation between NBR-dNBR and CBI are very diverse with determination coefficients ranging between 0.01 and 0.81 (Kasischke et al. 2008), the majority of studies have shown medium to high correlation values ($R^2 > 0.55$) (van Wagtendonk et al. 2004; Cocke et al. 2005; Epting and Verbyla 2005; Sorbel and Allen 2005). According to van Wagtendonk et al. (2004), the very low correlations can be explained by the non-linear relationship between CBI and dNBR, and the fact that there is a signal saturation when CBI scores are larger than 2.3. It should be noted that the majority of studies do not consider the Root Mean Square Error (RMSE) between observed and estimated values or the presence of systematic biases (deviation from the 1:1 linear regression) (De Santis et al. 2009).

Although there is an absence of relevant studies in the literature, the inconsistencies observed in the relationship between CBI and NBR can be attributed to the following causes:

*For colour version of this figure, please refer Colour Plate Section.

- CBI cannot properly be retrieved from reflectance measurements,
- NBR is not sensitive enough to CBI variations.

There are cases in which CBI is reported to be a good measure of burn severity, especially in boreal ecosystems (French et al. 2008), while in other cases it has been demonstrated that the NBR is not efficient in detecting changes between pre and post-fire reflectance (Roy et al. 2006).

The drawbacks of the dNBR and the CBI are that both are qualitative indices which are prone to subjectivity when they are stratified into burn severity classes (Lentile et al. 2006). Another drawback of the CBI is that it requires knowledge of the pre-fire conditions as all values are assigned based on the change in condition due to the fire. Hence, the CBI and dNBR most accurately assess the magnitude of change, rather than the current conditions on the ground (Robichaud et al. 2007).

De Santis and Chuvieco (2009) recently investigated the relationship between CBI and image reflectance values by employing sensitivity analysis and simulation models and proposing the Geometrically structured Composite Burn Index (GeoCBI), which is a modified version of the CBI which is computed as follows:

$$GeoCBI = \frac{\sum_{m_1}^{m_n} (CBI_m * FCOV_m)}{\sum_{m_1}^{m_n} FCOV_m} \tag{1}$$

where m is the identification of each stratum, and n is the number of strata.

According to De Santis and Chuvieco (2009), the GeoCBI improves the extraction of burn severity from remotely sensed data since it takes into account the cover fraction (FCOV) of the different vegetation strata used to compute the CBI as well as the changes in the Leaf Area Index (LAI) of the intermediate and tall tree strata (C, D and E). GeoCBI is reported to perform more accurately than the CBI when related to spectral reflectance and for a larger range of burn severities. It is also reported that the newly proposed index not only is a straight-forward approach but it does not lose its ecological meaning as well.

## 10.3 Burn Severity Estimation Using Remotely Sensed Data

Apart from the conduction of extensive field surveys, analysts use post-fire imagery to estimate burn severity in terms of soil and vegetation variations after fire (Clark and Bobbe 2006). The first type of imagery that was employed to assess fire effects was aerial photography. Observations on images acquired from airborne platforms were used to record burn severity and then map resource damage into predetermined classes (Bertolette and Spotskey 2001). Aerial photographs are increasingly being acquired and delivered in a digital format, which requires some image processing skills, such as the ability to georeference and ortho-rectify the images (Bobbe et al.

AQ7 2001). According to Clark and Bobbe (2006), aerial photography provides excellent spatial resolution and results in detailed images of burned areas. However, the main problem with the use of aerial photography is that each photograph usually covers a relatively small area, and many photographs are acquired in the case of large fires, which subsequently require correction and mosaicking.

In addition to aerial photographs, images acquired from satellite sensors have also been employed to estimate burn severity (Table 10.2). As early as 1974, Hitchcock and Hoffer state that computer-aided analysis of remote sensing data may discriminate distinct spectral classes within a burned area, which may indicate burn severity impact, the stage of re-vegetation, original cover type, or a combination of these three.

**Table 10.2** Examples of burn severity estimation studies using remotely sensed data

| Reference | Parameter(s) measured | Ecosystem | Sensor | Methods used |
|---|---|---|---|---|
| Benson and Briggs (1978) | Mapping the extent and intensity of major forest fires | Different types of Eucalyptus forest | Landsat MSS | Supervised and unsupervised classification |
| Bertolette and Spotskey (2001) | Burn severity mapping | Xeric shrublands | Landsat 7, SPOT 4 | Change detection, unsupervised classification, NDVI |
| Brewer et al. (2005) | Classifying and mapping wildfire severity | Temperate mixed Forests | Landsat TM | Evaluation of six different approaches using multi-temporal Landsat TM data (multi-temporal image differencing and rationing, multi-temporal principal component analysis, artificial neural networks) |
| Brumby et al. (2001) | Forest Fire Burn Severity Classification | Temperate coniferous forests | Landsat 7 ETM+ | Classification algorithms for multi-spectra imagery |
| Caetano et al. (1995). | characterizing burned areas and post-fire vegetation recovery | Temperate/ semi-arid shrubland | NOAA-AVHRR | Spectral mixture analysis |

**Table 10.2** (Continued)

| Reference | Parameter(s) measured | Ecosystem | Sensor | Methods used |
|---|---|---|---|---|
| Chuvieco and Congalton (1988) | Mapping and inventory of forest fires | Mediterranean Ecosystem | Landsat TM | Supervised classification, mixed supervised – unsupervised classification, NDVI |
| Chuvieco et al. (2006) | Simulate the postfire spectral response to burn severity | Simulated Mediterranean Ecosystem | Full spectrum | Use of a radiative transfer model |
| Chuvieco et al. (2007); De Santis and Chuvieco (2007, 2008); De Santis et al. (2009) | Initial assessment of the short-term burn severity | Mediterranean Ecosystems | Landsat TM, SPOT 5 | Use of a radiative transfer model, CBI and GeoCBI |
| Cocke et al. (2005) | Burn severity assessment | Temperate coniferous forests | Landsat ETM+ | Comparison of burn severity assessments using Differenced Normalized Burn Ratio (ΔNBR) and ground data |
| Díaz-Delgado et al. (2003) | Influence of burn severity on plant regeneration | Mediterranean forests, woodlands, and shrub | Landsat TM and MSS | NDVI |
| Epting and Verbyla (2005) | Assessing burn severity | Boreal forests | Landsat TM | Evaluation of vegetation indices |
| Escuin et al. (2002) | Assessing wildfire damage | Mediterranean forests, woodlands, and shrub | Landsat TM | Spectral Mixture Analysis |
| Fox III and Stuart (1994) | Detecting changes in forest condition following wildfire | Mediterranean forests, woodlands, and shrub | Landsat TM | NDVI |
| Jakubauskas et al. (1990) | Assessment of vegetation change in a fire-altered forest landscape | Temperate Coniferous Forests | Landsat TM | Comparison of pre-fire and post-fire maps |

**Table 10.2** (Continued)

| Reference | Parameter(s) measured | Ecosystem | Sensor | Methods used |
|---|---|---|---|---|
| Kasischke et al. (1994) | Remotely sensed data Intensity associated with Forest Fires | Boreal forests | ERS-1 SAR | Observation of variations in ERS-1 SAR image intensity |
| Kasischke et al. (2007) | Assessing spatial and temporal variations in surface soil moisture in fire-disturbed forests | Boreal forests | SAR | Spatial and temporal analysis of satellite data |
| Key and Benson. (2005). Key and Benson (2000) Key and Benson (2002a). | Assessing burn severity | Temperate Grasslands, Savannas, and Shrublands | Landsat TM | Composite Burn Index, Normalized Burn Ratio Composite Burn Index, Normalized Burn Ratio Composite Burn Index, Normalized Burn Ratio |
| Kokaly et al. (2006). | Characterization of post-fire surface cover, soils, and burn severity | Temperate Coniferous Forests | AVIRIS and Landsat Enhanced Thematic Mapper plus (ETM+) | Supervised classification (maximum likelihood) |
| Lachowski and Anderson (1979) | Assessment of fire damage | Northern mixed forest and string-bog habitat | Aerial photography and Landsat MSS | Image classification |
| Laes et al. (2004) | Post-fire burns everity classification | Temperate coniferous forests | Hyperspectral imagery collected by Earth Search Systems (ESSI) | Classification of hyperspectral data |
| Landmann (2003) | Characterizing sub-pixel Landsat ETM+ burn severity | tropical and subtropical grasslands, savannas, and shrublands | Landsat ETM+ | Linear spectral mixture model |
| Medler and Yool (1997). | Wildfire induced vegetation mortality | Temperate Coniferous Forests | Landsat TM | Combination of TM and digital terrain data, supervised classification |

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**Table 10.2** (Continued)

| Reference | Parameter(s) measured | Ecosystem | Sensor | Methods used |
|---|---|---|---|---|
| Miller and Thode (2007) | Quantifying burn severity in a heterogeneous landscape | Mediterranean forests, woodlands, and shrub | Landsat TM | Delta Normalized Burn Ratio (ΔNBR) |
| Mitri and Gitas (2008) | Mapping the severity of fire | Mediterranean forests, woodlands, and shrub | Ikonos | Object-based classification |
| Parsons and Orlemann (2002) | Mapping post-wildfire burn severity | Temperate coniferous forests | Landsat and SPOT | Image classification and GIS analysis |
| Patterson and Yool (1998) | Mapping fire-induced vegetation mortality | Temperate Coniferous Forests | Landsat TM | A comparison of linear transformation techniques |
| Redmond et al. (2001) | Classifying and mapping wildfire severity | Temperate Grasslands, Savannas, and Shrublands | Landsat TM | Multi-temporal image differencing, Principal Component Analysis (PCA) and hierarchical machine learning technology |
| Robichaud et al. (2007) | Post-fire soil burn severity mapping | Temperate coniferous forests | airborne hyperspectral imagery | Mixture Tuned Matched Filtering (MTMF) |
| Rodriguez y Silva et al. (1997) | Evaluation of fire damage | Mediterranean forests, woodlands, and shrub | Landsat TM | Spectral unmixing, vegetation indices |
| Rogan and Franklin (2001) | Mapping wildfire burn severity | Mediterranean forests, woodlands, and shrub | Landsat ETM+ | Spectral Mixture Analysis |
| Roy et al. (2006) | Assessing the performance of the normalized Burn ratio | Savanna, boreal forest, and tropical forest | Landsat ETM+ | Normalized Burn Ratio |
| Ruecker and Siegert (2000) | Fire Damage Assessment | Tropical and Subtropical Grasslands, Savannas, and Shrublands | ERS-2 SAR | Backscatter statistics |
| Siegert and Nakayama (2000) | Fire Impact Assessment | Tropical and Subtropical Grasslands, Savannas, and Shrublands | ERS-1/2 and JERS-1 | Backscatter statistics and Principal Component Analysis (PCA) |

**Table 10.2** (Continued)

| Reference | Parameter(s) measured | Ecosystem | Sensor | Methods used |
|---|---|---|---|---|
| Smith et al. (2005) | Estimating burn severity | African savanna | Earth Observation satellite imagery | Linear unmixing model |
| Sorbel and Allen (2005) | Burn severity mapping | Boreal forests | Landsat TM | CBI-Normalized Burn Ratio |
| Van Wagtendonk et al. (2004) | Burn severity mapping | Mediterranean forests, woodlands, and shrub | AVIRIS and ETM+ | Differenced Normalized Burn Ratio (ΔNBR) |
| Walz et al. (2007) | Classification of burn severity | The Mediterranean region of Western Australia | MODIS | Image classification |
| White et al. (1996). | Forest fire severity and vegetation recovery | Temperate Coniferous forests | Landsat TM | Analysis of change in reflectance values |

Although several of the parameters mentioned in the previous section may not be amenable directly to optical wavelength remote sensing, field-based measurements of burn severity have been used to parameterize and assess burn severity maps created using optical wavelength satellite data (Van Wagtendonk et al. 2004, Cocke et al. 2005). Moreover a number of methods were developed to estimate severity on the field and on satellite imagery (Ryan and Noste 1985; Cottrell 1989; Caetano 1995; Patterson and Yool 1998). As a result, a number of classification systems, which vary according to the ecosystem (vegetation types) under examination, were proposed. In general, each of these classification systems provided a physical description enabling assessment of the effects of fire on image scene components such as vegetation cover, crown area, soil cover, ground fuels and litter (Rogan and Yool 2001).

Following, the way remotely sensed imagery was employed in order to estimate burn severity is reviewed by taking into account differences in the type of ecosystem, the type of sensor and the image analysis technique employed.

### *10.3.1 Ecosystem*

Burn severity related studies have been carried out in a number of different ecosystems including:

- Temperate coniferous and mixed forests (Benson and Briggs 1978; Jakubauskas et al. 1990; White et al. 1996; Medler and Yool 1997; Patterson and Yool 1998; Brumby et al. 2001; Parsons and Orlemann 2002; Laes et al. 2004; Brewer et al. 2005; Cocke et al. 2005; Kokaly et al. 2007; Robichaud et al. 2007),
- Mediterranean forests and shrublands (Fox and Stuart 1994; Chuvieco and Congalton 1988; Rodriguez y Silva et al. 1997; Rogan and Franklin 2001; Escuin et al. 2002; Rogan et al. 2002; Díaz-Delgado 2003; Van Wagtendonk et al. 2004; De Santis and Chuvieco 2007; Miller and Thode 2007; Mitri and Gitas 2008; De Santis et al. 2009),
- Temperate grasslands and shrublands, (Key and Benson 2000, 2002a, b, 2005; Redmond et al. 2001),
- Semi-arid shrublands (Caetano et al. 1995; Bertolette and Spotskey 2001),
- Tropical and sub-tropical woodland and grassland savannas (Ruecker and Siegert 2000; Siegert and Nakayama 2000; Rogan and Yool 2001; Landmann 2003; Smith et al. 2005; Roy et al. 2006), and
- Boreal forests (Kasischke et al. 1994; Epting and Verbyla 2005; Sorbel and Allen 2005; Roy et al. 2006; Kasischke et al. 2007).

A review of the literature suggests that most research has so far been carried out in areas covered by temperate forests, as well as Mediterranean forests and shrublands. Also, independent of the study area, a strong relation between the type of ecosystem and the recovery time after fire has been recognized. As a result, the time of ground and image data acquisition depends greatly on the type of ecosystem.

### *10.3.2 Type of Sensor*

The majority of studies so far (Table 10.3) have been based on the use of the Landsat Multispectral Scanner (MSS) (Lachowski and Anderson 1979; Hall et al. 1980; Díaz-Delgado et al. 2003), the Landsat Thematic Mapper (TM) (Chuvieco and Congalton 1988; Hunt and Rock 1989; Jakubauskas et al. 1990; Fox and Stuart 1994; White et al. 1996; Rodriguez y Silva et al. 1997; Patterson and Yool 1998; Key and Benson 2000, 2002a, b, 2005; Redmond et al. 2001; Escuin et al. 2002; Key and Benson 2002a; Key et al. 2002; Miller and Yool 2002; Parsons and Orlemann 2002; Díaz-Delgado et al. 2003; Brewer et al. 2005; Epting and Verbyla 2005; Sorbel and Allen 2005; De Santis and Chuvieco 2007; Miller and Thode 2007; De Santis et al. 2009), and the Enhanced Thematic Mapper Plus (ETM+) imagery (Brumby et al. 2001; Rogan and Franklin 2001; Landmann 2003; Van Wagtendonk et al 2004; Cocke et al. 2005; Roy et al. 2005; Kokaly et al. 2006; Roy et al. 2006). Also the Landscape Assessment (LA), a part of the operationally used Fire Effects Monitoring and Inventory Protocol (FIREMON) which primarily addresses the need to identify and quantify fire effects over large areas, at times involving many burns, involves the use of Landsat 30-meter data (Key and Benson 2002a).

**Table 10.3** Examples of the number of identified burn severity classes and the type of sensor used

| Reference | Type of sensor | Number of identified burn severity classes |
|---|---|---|
| Benson and Briggs (1978) | Landsat MSS | 3 classes (lightly burn, moderate burn, severely burn) |
| Lachowski and Anderson (1979) | Landsat MSS | 6 classes (unburned, light surface burn, moderate surface burn, hard surface burn, shallow organic burn, deep organic burn) |
| Hall Landsat MSS et al. (1980) | Landsat MSS | 3 classes (light, moderate, and severe) as defined by the abundance of live post-fire vegetation |
| Díaz-Delgado et al. (2003) | Landsat MSS, TM | 7 classes (ground fire, canopy partially green with green leaves, burned trees with remaining burned leaves, burned trees with fine branches across the whole trunk, burned trees with fine branches only on top of the trunk, burned trees without fine branches, burned trees that only keep the trunk) |
| Chuvieco and Congalton (1988) | Landsat TM | Density slice of NDVI values from low to high (only in burnt areas) |
| Fox and Stuart (1994) | Landsat TM | 4 classes (light, moderate, severe, extreme) |
| Miller and Yool (2002) | Landsat TM, ETM+ | 4 classes (high, moderate, low severity and unburnt) |
| Rodriguez y Silva et al. (1997) | Landsat TM | 5 classes of damage (light, moderate, high, extreme I – all vegetation is scorched, extreme II – total combustion) |
| Patterson and Yool (1998) | Landsat TM | 3 classes (surface fire no or partial canopy destruction, complete canopy destruction organic matter in soil intact, complete canopy destruction organic matter in soil consumed) |
| Key and Benson (2000, 2002a, b, 2005); Key et al. (2002) | Landsat TM | 4 classes (low, moderate low, moderate high, high) |
| Redmond et al. (2001) | Landsat TM | 4 classes (lethal tree: the crowns of most, if not all, trees were burned, so that tree mortality was presumed to be high – Mixed Tree: the understory burned extensively, but the crowns of at least the larger trees weren't burned – Shrub: the predominant vegetation was comprised of shrubs that were burned extensively – Grass: the predominant vegetation was comprised of grasses and forbs that were burned extensively or completely) |

**Table 10.3** (Continued)

| Reference | Type of sensor | Number of identified burn severity classes |
|---|---|---|
| Escuin et al. (2002) | Landsat TM | 3 classes (no damage, moderate, extreme) |
| Parsons and Orlemann (2002) | Landsat TM and SPOT | 4 classes (unburned, low, moderate, high) |
| Brewer et al. (2005) | Landsat TM | 4 classes (lethal tree, burned shrub, burned grass, mixed lethal tree) |
| Epting and Verbyla (2005) | Landsat TM | 4 classes (high, moderate, low severity and unburnt) |
| Sorbel and Allen (2005) | Landsat TM | 5 classes (unburned, low, low moderate, high moderate, high) |
| De Santis and Chuvieco (2007) | Landsat TM | Full range of CBI (from 0 to 3) |
| Miller and Thode (2007) | Landsat TM | 4 classes (high, moderate, low severity and unburnt) |
| De Santis et al. (2009) | Landsat TM, SPOT 5 | Full range of GeoCBI (from 0 to 3) |
| Brumby et al. (2001) | Landsat ETM+ | 2 classes (high, low/unburned) |
| Rogan and Franklin (2001) | Landsat ETM+ | 3 classes (severe burn, mixed burn high vegetation cover, mixed burn low vegetation cover) |
| Van Wagtendonk et al. (2004) | Landsat ETM+ and AVIRIS | 4 classes (high, moderate, low severity and unburnt) |
| Cocke et al. (2005) | Landsat ETM+ | 4 classes (high, moderate, low severity and unburnt) |
| Kokaly et al. (2006) | Landsat ETM+, AVIRIS | 4 classes (high, moderate, low severity and unburnt) |
| Roy et al. (2006) | Landsat ETM+ and MODIS | The combustion completeness (cc) and the areal proportion that burned (f) |
| Walz et al. (2007) | MODIS | 4 classes (high, moderate, low severity and unburnt) |
| Bertolette and Spotskey (2001) | SPOT | 6 classes (no burn, slight, low, moderate, high, extreme) |
| Mitri and Gitas (2008) | Ikonos | 3 classes (slightly burned, moderately burned, heavily burned) |
| Ruecker and Siegert (2000) | ERS – SAR | 5 classes (unburned, 25–50% damage, 50–80% damage, >80% damage standing, >80% damage burned) |
| Siegert and Nakayama (2000) | ERS – SAR | 4 different damage levels: 0–25%, 25–50%, 50–80% and >80% |
| Kasischke et al. (2007) | ERS – SAR | 2 classes: burned and unburnt, and several parameters as biomass and Spruce recruitment (% of pre-burn). |

Mapping burn severity from remotely sensed data also includes the use of images acquired by the following sensors:

- Advanced Very High Resolution Radiometer – AVHRR (Chuvieco and Martin 1994; Caetano et al. 1995; Barbosa et al. 1999),

- Moderate-resolution Imaging Spectroradiometer – MODIS (Walz et al. 2007),
- Satellite Pour l'Observation de la Terre – SPOT (Henry and Hope 1998; Bertolette and Spotskey 2001; Parsons and Orlemann 2002; De Santis et al., 2009),
- Airborne Visible/Infrared Imaging Spectrometer – AVIRIS (Riaño et al. 2002; Van Wagtendonk et al. 2004; Kokaly et al. 2006),
- IKONOS (Mitri and Gitas 2008),
- European Remote Sensing satellite (ERS-1 and ERS-2) Synthetic Aperture Radar – SAR (Kasischke et al. 1994; Ruecker and Siegert 2000; Siegert and Nakayama 2000; Kasischke et al. 2007)

However, acceptable results have not always been obtainable. This can be mainly attributed to the insufficient spectral and spatial resolutions. According to Rogan and Franklin (2001), the main problems incurred when mapping post-fire effects from satellite imagery are as follows:

- spectral confusion between vegetation affected by surface fire and unburned vegetation;
- spectral confusion between moderately burned vegetation and sparse vegetation; and
- spectral confusion between burned shaded and unburned shaded vegetation.

Recently, the development of new sensors has made available new types of satellite data with improved spatial (e.g. IKONOS, Quickbird) and spectral resolutions (e.g. AVIRIS, EO-1 Hyperion, PROBA). Indeed, satellite data, whose high spatial resolution is comparable with that of an aerial photo, has made it possible to detect small objects not captured by medium-high resolution sensors. According to van Wagtendonk et al. (2004), one major application in which very high resolution imagery is expected to bring new insight is in the provision of post-fire related information. Also, Mitri and Gitas (2008) reported the successful mapping of burn severity by employing post-fire IKONOS imagery.

Hyperspectral sensors collect high spectral resolution data that can distinguish finer surface features than can broadband satellite imagery and may be able to better distinguish postfire ground cover and conditions (Robichaud et al. 2007). van Wagtendonk et al. (2004) calculated a multi-temporal band ratio similar to dNBR using AVIRIS hyperspectral bands (788 and 2370 nm), showing that the ratio between higher spectral resolution data may have the potential to be slightly more sensitive to fire effects than are traditional broadband ratios. Also Laes et al. (2004) classified burn severity by employing Probe 1 hyperspectral imagery. The aforementioned studies illustrated the potential advantages of using higher spectral resolution and suggested exploiting the discriminatory power of hyperspectral imagery for postfire assessment.

Apart from information collected in the visible and near-infrared (NIR) parts of the spectrum, information collected in the thermal infrared by sensors such as MODIS and SEVIRI (Roberts et al. 2005; Wooster et al. 2005) have also been used to estimate Fire Radiative Energy (FRE) which has proven to be proportional to

the fuel consumption and therefore to burn severity. Finally, Light Detection And Ranging (LIDAR) sensors that use laser pulses to determine the distance to an object or surface have been successfully used in fuel type mapping (Riaño et al. 2007) and biomass estimation (Van Aardt et al. 2006). It is expected that the collection of LIDAR images before and after a fire event will result in accurate estimation of burn severity.

### *10.3.3 Image Analysis Technique*

Since the mid 1980s, numerous image analysis techniques have been developed in order to map burn severity from remotely sensed data. These techniques include vegetation indices, image transformations, image classifications, and radiative transfer models. The way these techniques were employed is discussed, in turn, below.

#### 10.3.3.1 Vegetation Indices

The observation of broad spectral changes due to burning has led to the use of a variety of spectral indices, i.e. combinations of different sensor bands, in burn severity mapping including:

- simple Near InfraRed (NIR) to Red ratios (Jakubauskas et al. 1990),
- the Normalized Difference Vegetation Index – NDVI (Fox and Stuart 1994; Caetano et al. 1995; Rodriquez y Silva et al. 1997; Rogan and Yool 2001; Escuin et al. 2002; Cocke et al. 2005),
- the Soil Adjusted Vegetation Index (SAVI) and the Modified SAVI (Rodriguez y Silva et al. 1997; Rogan and Yool 2001), and
- the Atmospherically Resistant Vegetation Index – ARVI (Rodriquez y Silva et al. 1997)

More recently, it was observed that the near-infrared (NIR) and the mid-infrared (MIR) parts of the spectrum are particularly sensitive to fire induced changes in vegetation and soil (van Wagtendonk et al. 2004; Lutes et al. 2006). A decrease in green vegetation and vegetation moisture, due either to fire or to vegetative productivity, causes NIR to decrease with burn severity, while MIR increases because of the decrease in moisture and increased exposure of soil and rock and fewer shadows from trees (Lutes et al. 2006; Robichaud et al. 2007). As a result, the Normalized Burn Ratio (NBR), and the differenced Normalized Burn Ratio (dNBR) are used as indices of burn severity (Key and Benson 2002a; Lutes et al. 2006). NBR values are:

- strongly positive when vegetation is green and thriving,
- near zero when vegetation is sparse or senesced, and
- negative when soil exposure is high and there is little or no green vegetation (such as after a recent fire).

- Similarly, dNBR is also driven by green vegetation and soil exposure, at either end of the burn severity spectrum, but since the pre- and postfire values are differenced, low dNBR values indicate low burn severity and high dNBR values indicate high burn severity (opposite of NBR).

A number of studies have been carried out to assess the quantitative, physical characteristics of NBR and dNBR classes on the ground (Key and Benson 2000, 2005; Miller and Yool 2002; van Wagtendonk et al. 2004; Brewer et al. 2005; Epting and Verbyla 2005; Sorbel and Allen 2005; Roy et al. 2006; Chuvieco et al. 2006; Kasischke et al. 2007; Miller and Thode 2007; Walz et al. 2007). As mentioned in the previous section, evaluation was made through comparisons with the CBI and medium to high correlation values were obtained.

#### 10.3.3.2 Image Classification

Multispectral classification is one of the most frequently methods used to extract information from satellite data. Supervised and unsupervised classifications are the most common classification procedures employed to map burn severity (Hitchcock and Hoffer 1974; Benson and Briggs 1978; Lachowski and Anderson 1979; Chuvieco and Congalton 1988; Jakubauskas et al. 1990; Bertolette and Spotskey 2001; Brumby et al. 2001; Escuin et al. 2002; Kokaly et al. 2006). In a number of cases, products resulting from image transformations such as the Principal Components Analysis (PCA) and the Kauth-Thomas (KT) (Rogan and Yool 2001; Rogan et al. 2002) as well as vegetation indices such as the NDVI (Patterson and Yool 1998) were added to the dataset as extra bands before the application of classification.

Apart from supervised and unsupervised classification, density slicing has also been employed to map burn severity. This is the case with Hall et al. (1980) who classified multi-temporal Landsat MSS data of tundra fires in northwestern Alaska into light, moderate, and severe fires as defined by the abundance of live post-fire vegetation. It should be noted that density slicing has been applied on single bands (Key and Benson 2005), as well as on vegetation indices such as the NDVI (Fox and Stuart 1994). In addition to the techniques mentioned above, machine learning methods, such as Artificial Neural Networks (ANN), were applied both on single post-fire imagery and on multi-temporal pre- and post-fire imagery by Brewer et al. (2005) and accurate maps of burn severity were produced.

The accuracy of burn severity mapping by employing image classification has been reported (Brumby et al. 2001) to be affected by:

- the spectral overlapping between slightly burned areas and other non-vegetation categories, especially bare soil, and
- confusion caused by dark cloud shadows and by bare ground/rock outcrops which are physically very similar to the charred remains of the severely burned forest.

To overcome these problems, object-based image analysis was also recently investigated by Mitri and Gitas (2008) for use in mapping burn severity and resulted

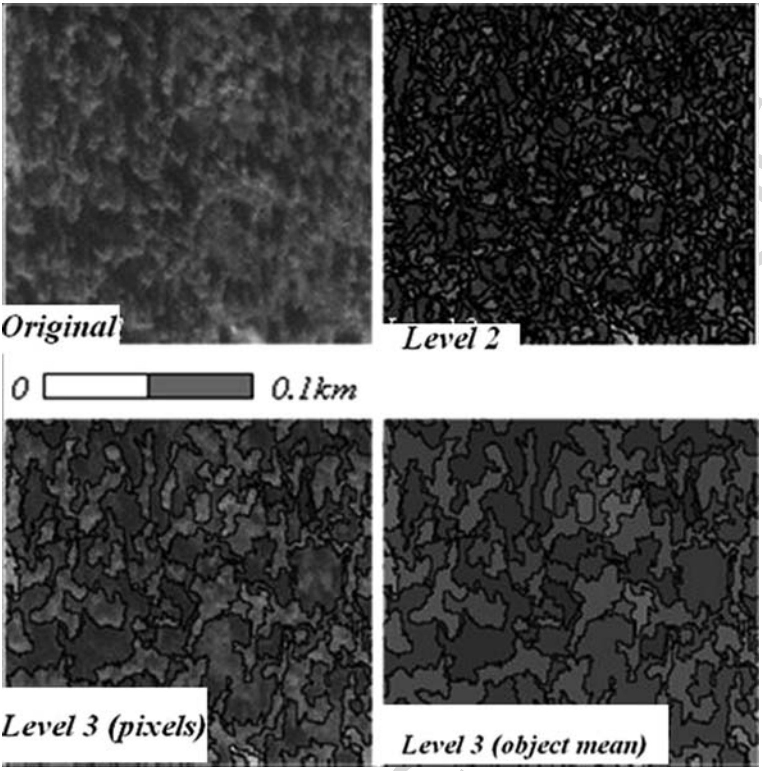


**Fig. 10.2** Example of object oriented image analysis, Mitri and Gitas (2006)

in the accurate mapping of the relevant classes (Fig. 10.2). Object-based classification deals with objects, i.e. a group of pixels that are generated by image segmentation, and is able to use both spectral and contextual information (Mitri and Gitas 2006). According to Wicks et al. (2002), object-based classification may result in increased accuracy, a more appropriate and realistic representation of the environment and a powerful and flexible framework for further data analysis.

#### 10.3.3.3 Radiative Transfer Models

AQ12

The use of Radiative Transfer Models (RTMs) has been reported to increase the accuracy of burn severity estimation when compared to more traditional techniques (Chuvieco et al. 2007; Chuvieco et al. 2006; De Santis and Chuvieco 2007). RTMs simulate spectral signatures from a set of input parameters at both leaf and canopy level. In the forward simulation mode, RTMs are used to analyse the effects of such plant parameters on spectral reflectance, whereas, in the inverse mode, spectra (from remotely sensed data) are used as an input to estimate some of those plant parameters (output).

More specifically, in the case of burn severity estimation:

- In the forward mode, the models attempt to reproduce all possible combinations of damage occurred in the different vertical vegetation strata (substratum, understory, overstory). This results in a collection of spectra (Look Up Table, LUT) which correspond to several values of burn severity.
- In the inverse mode, the LUT is compared to the spectral signature of each pixel of the satellite image. When the most similar spectrum is found, the correspondent value of burn severity is assigned to the pixel resulting in the production of a burn severity map (Fig. 10.3).

RTMs were initially employed by Chuvieco et al. (2006) to simulate burn severity scenarios (in terms of CBI). Following, the proposed model was inverted resulting in more accurate estimations of burn severity (De Santis and Chuvieco 2007). More recently, the accuracy of burn severity estimation was further improved when geometric models and GeoCBI were employed (De Santis et al. 2009).

#### 10.3.3.4 Other Techniques

Apart from the aforementioned techniques, image transformations such as the Principal Components Analysis, the Kauth-Thomas (KT) and Spectral Mixture Analysis

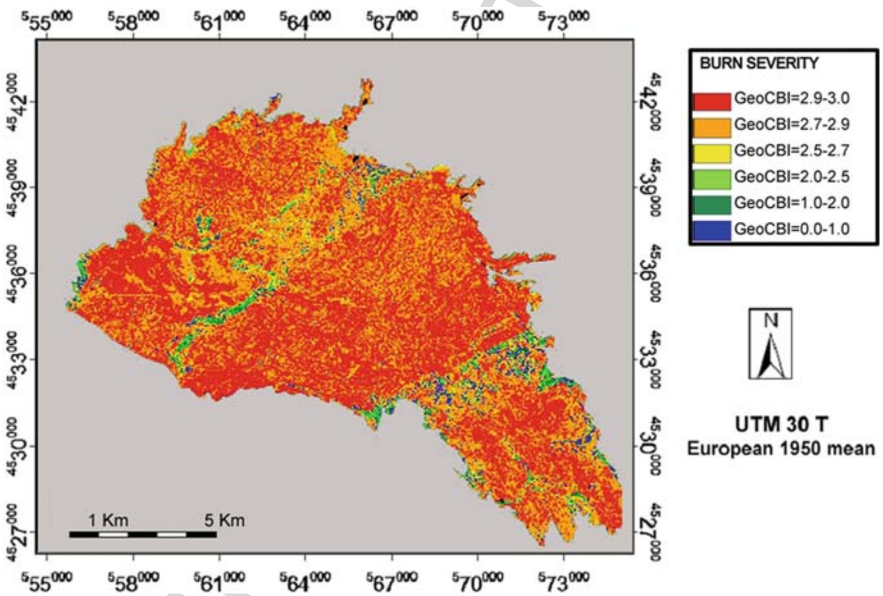


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**Fig. 10.3** Example of a burn severity map obtained from the inversion of the simulation model proposed by De Santis et al. (2009)*

*For colour version of this figure, please refer Colour Plate Section.

(SMA) as well as simple image differencing, have also been applied in order to map burn severity. More specifically, the multi-temporal application of PCA and KT on pre-fire and post-fire imagery is reported to produce accurate maps of burn severity (Redmond et al. 2001; Rogan and Yool 2001; Rogan et al. 2002). Similarly, SMA (Caetano et al. 1995; Rogan and Franklin 2001; Rogan et al. 2002) has also been reported to successfully estimate burn severity, both when a linear spectral mixing model (Landmann 2003; Smith et al. 2005) or when a partial spectral unmixing algorithm such as the Mixture Tuned Matched Filtering (MTMF) (Robichaud et al. 2007) is employed. In addition, mage differencing was applied both on single post-fire imagery and on multi-temporal pre-fire and post-fire imagery by Brewer et al. (2005) who produced accurate maps of burn severity.

## 10.4 Future Investigation

Future research related to remote sensing of burn severity is expected to focus on the following:

- Careful evaluation of existing operational procedures (e.g. Landscape Assessment) that identify and quantify burn severity over large areas and different ecosystems; if necessary, modification of existing procedures and development of new ones to be used at local, regional, and national levels.
- Continuation of the development of quantitative methods for burn severity estimation on the ground and on satellite imagery.
- Continuation of the development of methods to estimate burn severity at a global level in order to produce more accurate estimates of $CO_2$ emissions due to fires.
- Exploitation of data acquired by sensors with different characteristics suitable for studying aspects of fire that are already available (e.g. LIDAR) or will become available in the near future such as the EnMAP (Environmental Mapping and Analysis Program) hyperspectral imager (a 30-m resolution satellite sensor to be launched by DLR in 2012) in order to improve burn severity estimation. Also the use of combined data acquired from more than one sensor.
- Exploitation of advanced image analysis techniques in order to develop automated and transferable procedures.

## 10.5 Summary – Conclusions

Based on a review of the literature, a number of conclusions can be drawn:

- The role of remote sensing is increasingly becoming very important in the estimation of burn severity.
- More detailed information about a burn scar is desired in order to estimate burn severity than when mapping the presence/absence of fire.

- Burn severity estimation on the ground is increasingly being based on the use of indices which have recently been developed in order to quantify the fire effects and ensure consistent and comparable estimations of burn severity across broad geographic regions. These indices have the possibility to be used complementary to remotely sensed data.
- Most research has so far been carried out in areas covered by temperate forests, as well as by Mediterranean forests and shrublands. Independent of the ecosystem, accurate estimation of burn severity is strongly related to the time of ground and image data acquisition which, in turn, depends greatly on the type of ecosystem.
- Although a number of different sensors have so far been employed for mapping burn severity, the majority of studies have been based on the use of Landsat TM data. Therefore, the use of recently developed sensors that produce images with improved spatial and spectral resolutions should be further investigated.
- The main techniques employed so far are vegetation indices, image transformations, image classifications, and radiative transfer models. Independent of the technique employed, the tendancy in recent years is that remotely sensed data are used in association with quantitative measurements of burn severity on the ground.
- A number of developments such as: the production of (quantitative) field protocols, the increase in the number of sensors with different characteristics suitable for studying aspects of fire, the improved access to and availability of satellite data and derived products, and the development of new methods and advanced digital image analysis techniques are expected to move forward research as well as the operational use of remote sensing in burn severity estimation and mapping.

# Chapter 10

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| AQ4 | Please specify whether “Chuvieco et al. 2007” is “2007a” or “2007b”. |
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| AQ10 | Au: "Kokaly et al. 2006" is not listed in the reference list. Please provide. |
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| AQ12 | Au: Please specify whether “Riaño et al. 2007 “is “2007a” or “2007b”. |
| AQ13 | Au: Please specify whether “Chuvieco et al. 2007” is “2007a” or “2007b”. |

# Chapter 11
# Human Factors of Fire Occurrence in the Mediterranean

**Vittorio Leone, Raffaella Lovreglio, M. Pilar Martín, Jesús Martínez, and Lara Vilar**



**Abstract** The Mediterranean region accounts the larger proportion of human caused fires in the world (95%) followed by South Asia (90%), South America (85%) and Northeast Asia (80%) (FAO 2007). Socio-economic changes which are occurring in Europe along with global warming result in an augment of fire risk. Systematic and reliable information on fire causes is necessary in order to improve wildland fire management. However, collection of information on forest fire causes and motivations is still quite restricted in most countries around the world. The unknown cause is still too frequent in many wildfire statistics. A promising technique to overcome this shortcoming is the Delphi technique which uses a panel of carefully selected experts to improve the knowledge on fire motivations in a specific area. Understanding more about why people start fires would help to reduce the impacts of deliberate fire lighting. Spatial and temporal analysis of wildland fire occurrence data and the interaction with explanatory geographical variables is a critical part of fire management activities. Geographic Information Systems (GIS) are appropriate tools to create, transform, combine and integrate variables related to fire risk in order to find geographical and analytical relationships which help to discriminate areas where risk factors are most severe in order to adopt the appropriate preventive actions.

## 11.1 Fire as an Anthropogenic Phenomenon

The practice of burning natural vegetation with different purposes has very remote origins. Along the history, fire has been in use in some socioeconomic systems as a way for regenerating the pastures, eliminating harmful animal species, suppressing the natural vegetation to implement crops, etc. Some of these activities (i.e. slash and burn agriculture) continue being practiced in diverse zones of the Planet

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(principally in tropical areas) by small producers, peasants and indigenous peoples, among whom the burning of the forest for the conquest of new spaces suitable for the agriculture has a long tradition (Fujisaka et al. 1996; Tinker et al. 1996). Along with the land clearing activities, the main anthropogenic causes of forest fires in the tropics are related with land tenure or land use disputes, accidental or escaped fires and fires connected with resource extraction (Nepstad et al. 1999; Barber and Schweithelm 2000; Applegate et al. 2001). Land development tactics, such as ranching in Amazonia (Nepstad et al. 1999) or pulp or oil palm plantations in Indonesia (Barber and Schweithelm 2000; Applegate et al. 2001) use fire for land preparation and have significantly contributed to wildland fires. Additionally, small farmers use fire in the preparation of land for permanent crops or agriculture. These land-clearing fires often escape the intended area of burn spreading to nearby forests. On the other hand, arson is a major cause of fire in many resource-rich areas, where land is either scarce for agricultural production and/or where there are resource conflicts over land tenure or access rights (Applegate et al. 2001).

In other areas, such as the Mediterranean, fire nowadays does not form a significant part of traditional systems of life, however it continues turning out to be strongly tied to the human activity. Socio-economic changes which are occurring in Europe (abandonment of agricultural land, depopulation of rural areas, priority shifts in forestry policy, disinterest in the forest as a resource, etc.) result in an augment of unmanaged shrubs and biomass which increases fire risk (Vélez 2004). These factors are also aggravated by climate conditions as Mediterranean areas are characterized by hot and dry summers, associated with high levels of fire hazard. Furthermore, research on climate change indicates that increased fire hazard is likely to arise from global warming (Westerling et al. 2006; Running 2006). The seriousness of the problem is due to the fact that natural causes have been compounded by human action (negligence, accidents, burning as an agricultural or grazing practice and arson) altering natural fire regimens and increasing the adverse consequences of fire on society and the environment (damage to human health and properties, loss of biodiversity, increase of the risk of floods and soil erosion, contribution to the greenhouse effect, etc.).

In spite of the severe social, economic and environmental impacts of fire, consistent and reliable information on fire incidence, causes and impacts is still noticeably insufficient, especially at regional and global scales. As we will discuss in the next section, statistics on the causes of forest fires in the Mediterranean region are incomplete. However, data available evidence that a great majority of fires are due to anthropogenic factors and only a small percentage is caused by natural agents such as lightning. The FAO Fire Management and Global Assessment 2006 Report (FAO 2007) elaborated from 12 regional working papers prepared within the framework of the Global Wildfire Network of the United Nations International Strategy for Disaster Reduction, offers some rough estimations on fire causes in the world. According to this report, the Mediterranean region accounts the larger proportion of human caused fires in the world (95%) followed by South Asia (90%), South America (85%) and Northeast Asia (80%). Only in very remote areas in Canada and the Russian Federation is lightning the major cause of fires.

The set of human causes is large and complex and they are often indicators of conflicts and tensions in the overall system of land management. In the FAO report (FAO 2007) land clearing and other agricultural activities along with negligence and arson were the most commonly mentioned anthropogenic fire causes. However, under this generic classification a great diversity of more specific causes and motivations reveals the enormous complexity of the problem. In such scenario, action measures to be taken should go far beyond forest activities and tackle the specific causes of fire related to economic, legal, and even cultural as well as behavioural factors.

## 11.2 Sources of Information on Wildfire Causes in Euro-Mediterranean Countries

Systematic and reliable information on fire causes is necessary in order to improve wildland fire management. Accurate information on fire causes would help to reliably predict where, when, why and how many fires are likely to occur. Such information would allow fire and landscape management authorities to take on a more "pro-active" planning approach (fire prevention) than in the present situation where it is usually a "reactive" process (fire fighting) (Leone et al. 2003). However, this fact contrast with the limited information available on fire causes at the global level and also in most European countries/regions. The unknown cause is still too frequent in many wildfire statistics. Table 11.1 shows the percentage of forest fires due to unknown causes in some European countries from 1999 to 2001 (FAO 2002). As it can be observed, in most of the countries the percentage of unknown causes have risen above 50% and in many of them it reaches up to 70% or 80%.

The systematic collection of information on forest fire causes is still quite restricted in most countries around the world. Most statistical data are in the "grey literature" and practically unavailable for international interpretation. The increasing interest in analyzing fire trends on a supranational scale has kept a number of international institutions such as FAO, United Nations and European Union working to compile fire statistics of the last decade. A first global attempt to collect country reports and to summarize information on wildfires causes is the joint FAO/ECE Working Party on Forest Economics and Statistics who has carried out, since 1980, enquiries on forest fire statistics in the countries of the United Nations Economic Commission for Europe with the approval of its parent bodies, the ECE Timber Committee and the FAO European Forestry Commission. The results are published annually under the title "Forest Fire Statistics" in the Timber Bulletin and are also available for the period 1994–2001 at the Timber Committee web site http://www.unece.org/timber/ff-stats.html. Those reports provide statistics on forest fires in the UNECE region, Europe, North America and the countries of the CIS (former Soviet Republics). Between 20 to 37 countries (depending on the year) replied to the enquiry. The statistics include number and size of fires by forest types and causes. The information provided in this document offer a reasonable coverage

**Table 11.1** Percentage of forest fires of unknown cause in European countries (1999–2001)

| Country | 1999 | 2000 | 2001 |
|---|---|---|---|
| Belarus | 27.4 | 33.6 | ND |
| Belgium | 50.0 | 100.0 | 25.0 |
| Bulgaria | 70.9 | 76.4 | 75.0 |
| Croatia | 57.8 | 73.5 | ND |
| Cyprus | 55.0 | 28.1 | 29.8 |
| Czech Rep. | 34.4 | 36.0 | ND |
| Denmark | ND | ND | 50.0 |
| Estonia | 10.8 | 33.5 | ND |
| France | 67.7 | 76.6 | 53.1 |
| Germany | 42.7 | 43.7 | 34.1 |
| Greece | ND | ND | 75.2 |
| Kazakhstan | 89.9 | 87.0 | ND |
| Lithuania | 5.5 | 5.4 | 3.1 |
| Norway | 78.4 | 77.3 | ND |
| Poland | 72.5 | 64.6 | ND |
| Portugal | ND | ND | 96.4 |
| Romania | 41.7 | 34.9 | ND |
| Russian Federation | 10.7 | 13.8 | ND |
| Serbia & Montenegro | 28.0 | 66.1 | 47.9 |
| Slovakia | ND | 4.5 | ND |
| Slovenia | 49.1 | 45.9 | ND |
| Spain | 20.2 | 16.7 | 35.8 |
| Sweden | ND | ND | 38.8 |
| Switzerland | 26.8 | 0.0 | ND |
| Turkey | 21.3 | 18.1 | 21.4 |
| Ukraine | 0.2 | 0.4 | 0.6 |

Source: United Nations Forest Fire Statistics. ECE/TIM/BULL/2002/4 http://www.unece.org/trade/timber/ff-stats.html ND: No data

of forest fires in Europe, as the great majority of fires occur in the Mediterranean region, for which most of the data were available. The data for North America and the countries of the former USSR also provide a good coverage of the forest fire situation. The information is obtained mainly from official national sources.

Another source of information on global fire statistics is the FAO Global Forest Fire Assessment 1990–2000, part of the FAO Forest Resources Assessment (FAO, 2001) published online as Working Paper No. 55 (http://www.fire.uni-freiburg.de/programmes/un/fao/Wp55_eng.pdf). The Global Fire Assessment includes statistical data from Europe but no quantitative information on fire causes is available.

AQ1 More recently, within the FAO Forest Resources Assessment 2005 (FAO 2005) regional reports on forest fires were written by representatives of the Regional Wildland Fire Networks. Those reports were complemented by a more in-depth thematic study, the Fire Management Global Assessment 2006 (FAO 2007) which includes information on fire incidence, impact and management in different regions with specific sections on fire causes. Contributors to this report highlight the great challenge

that supposes to gather reliable and updated information on wildland fires at a global scale and encourage readers to provide feedback (comments and/or data) to improve the knowledge of the phenomenon.

In Europe, the First Ministerial Conference on the Protection of Forests which took place in Strasbourg (France) in December 1990 agreed on the increasing threats to European forests and recognized the need for cross-border protection. This Strasbourg Conference initiated a broad scientific and technical cooperation throughout Europe and addressed the establishment of a Decentralized European Data Bank on Forest Fires. The Commission of the European Communities, on the basis of Council Regulation (EEC) Nº 2158/92 (July 1992) on protection of the Community′s forests against fire decided that Member States must, at least, collect a set of data consisting of fire statistical information, comparable on a community level and accessible at specified regular intervals. Rationale and principles of the database are described in Commission Regulation (EC) Nº 804/94 of 11 April 1994 (now expired). Annex I of this document details the minimum common core of information on forest fires that each officially recorded forest fire must include. One of the required facts is forest fire causes. According to the mentioned regulation the presumed cause of the fire should be indicated according to the following four categories:

1. Cause of fires unknown;
2. Natural cause, e.g. lightening;
3. Accidental cause or negligence, i.e. the origin is connected directly or indirectly with a human activity but the person concerned did not act with the intention of destroying an area of forest (e.g. accidents caused by power lines, railways, works, barbecues, a bonfire that got out of control, etc.);
4. Fires started deliberately, i.e. by someone intending to destroy an area of forest for whatever motive.

According to the currently in force Forest Focus Regulation (EC) No 2152/2003, concerning monitoring of forests and environment interactions in the Community, the forest fire common core data should continue to be recorded and notified in order to collect comparable information on forest fires at Community level. The forest fire data are, therefore, provided each year by individual Member States, checked, stored and managed by the Joint Research Center within the European Forest Fire Information System (EFFIS). At present the database covers seven Member States of the Union with fire-risk areas: Portugal, Spain, France, Italy and Greece (data available from 1985 to 2001), Germany (1994–2001) and Cyprus (2000–2001).

At a national level, administrative organizations in charge of forest fire fighting tend to follow a data acquisition protocol regarding fire occurrence. Two data acquisition mechanisms are often used. First, a simple system in the form of preliminary statistics that may enable a quick assessment of the forest fires using basic variables (number of fires, area affected, etc.). Second, a more elaborate tool (forest fire database) that usually includes the use of standard forms for data collection, which provide a more detailed knowledge of the problem and its outcomes and can

thus enlighten aspects on fire fighting. The quantity and quality of the information collected in these national databases, as well as its time span, varies considerably among countries in the Mediterranean basin. In any case, whatever their deficiencies, these databases constitute a reference point in order to obtain information of the causes of fires providing a global perspective on factors influencing fire occurrence in the European Mediterranean basin as a whole, and nations and regions in particular.

Most of the databases mentioned, including the ones at a national level are available through the Global Fire Monitoring Center (GFMC) an activity of the UN International Strategy for Disaster Reduction (ISDR) which provides a global portal for wildland fire documentation, information and monitoring publicly accessible through the Internet (http://www.fire.uni-freiburg.de/).

## 11.3 Fires and Motivations Behind Causes in the Mediterranean

Unlike other parts of the world, where a large percentage of fires are of natural origin (especially lightning), the Mediterranean basin is marked by a prevalence of human-induced fires. Natural causes represent only a small percentage of all fires (from 1 to 5 percent, depending on the country) (Alexandrian et al. 1999).

The anthropogenic causes related to fire occurrence are habitually sorted in two main groups, depending on the existence or not of intentionality. The first group includes actions which directly or indirectly cause fire ignition and/or facilitate fire propagation in absence of intentionality. In this case fires are commonly a result of negligence and/or accidents. In the second group are included those actions that generate the meaningful beginning of a fire.

At a Mediterranean scale we are witnessing today a drop in fires of agricultural origin, i.e. a traditional instrument of agricultural management, and their replacement with involuntary fires, often testifying the slight familiarity towards nature of people no more issued by a rural society. Fires started by accidental causes or negligence, i.e. whose origins are connected directly or indirectly with a human activity, but the person concerned did not act with the intention of destroying an area of forest, are rather numerous and have some specific features and characteristics of repetition, concentration, distribution pattern and relationship with human seasonal activities (for instance agricultural, recreation activities etc.). At the same time, the increasing trend in voluntary fires has become more marked. This is an undeniable reality, grown to relevant proportions, sometimes proved by the capture of confessed authors and by the finding of primitive (but not for this less efficient) delayed time incendiary devices, indicating the wish to carry through the destructive act, carefully choosing the place, time and method of ignition (Leone 2000).

Social and economic changes in Western Europe have led to a transfer of population from the countryside to the cities, an abandonment of lands and a disinterest in the forest resource as a source of energy. This has resulted in the expansion of unmanaged wooded areas, erosion of the financial value of the wooded lands, a loss

of inhabitants with a sense of responsibility for the forest and, what is important, an increase in the amount of fuel. Paradoxically the fundamental cause of forest fires seems linked to increased standards of living (Alexandrian et al. 1999).

Surely we now perceive fires as a negative factor menacing the forest and its diverse functions; but we forget that, in a rather recent past, people considered the forests like an obstacle for development, without attention for its ecological values. In those times people only recognised the value of alternative uses for the space that the forest occupied; if they burned it, there would be more space for agriculture and farming (Leone and Lovreglio 2003).

There are few forces more potentially destructive than fire and perhaps none that can be so easily created and released. Fire is actually unique in its ability to put power in the hands of an otherwise disempowered person. The deliberate lighting of a fire can be an action with multiple elements and purposes (Willis 2004). The impulses that prompt people to destroy their environment, i.e. the inner drives or impulses that are the cause, reason or incentive that induce or prompt a specific behavior (Jackson and Fisher 2001) are often retrievable as a list of possible motivations, for instance:

- Perverse economic and social incentives that encourage the inappropriate use of fire.
- Greed and corruption.
- Land and resource conflicts.
- Weak or ineffective bureaucracies and governments.
- Economic necessity.
- Political motives.

In a detailed review of arson by Willis (2004), the author concludes that, when taken as a whole, the literature suggests the following common motives for arson:

- Revenge, usually against an employer, lover or institution.
- Excitement or relief of boredom.
- Vandalism, often influenced by peer pressure.
- Financial gain, including insurance fraud and for other business purposes.
- Attention-seeking, including as a “cry for help” or to gain recognition and “hero status”.

Willis suggests a typology of arson consisting of five principal types of deliberately lit wildfires:

- To create excitement or relieve boredom.
- For recognition and attention.
- For a specific purpose or gain.
- Without motive.
- With mixed motives.

Classifications as abovementioned were conceived for the specific reality of Australia where bushfires are a fact of life. Much of the nation's population lives in areas where the threat of bushfire is an ever present reality and the country can be considered the most fire-prone area on Earth (Willis 2004). Such classifications anyway help to replace simple lists of motivations with much more plausible behaviors related to fire.

In this sense, a very interesting taxonomy of arson motivations, able to identify the inner drives, the personal traits and characteristics exhibited by offenders, was proposed by Douglas et al. (1992) working at the National Center for the Analysis of Violent Crime (NCAVC) of FBI Academy in Quantico, Virginia. They reviewed arson research literature, actual arson cases and interviewed incarcerated arsonists across the nation, producing a motive classification which proves very effective in identifying offender characteristics:

- Vandalism: Malicious or mischievous fire setting that results in damage to property: willful and malicious mischief or peer group pressure.
- Excitement: Seeking of thrill, attention, recognition, sexual gratification (rare), relieve of boredom. Fires are set to gain attention and to meet the needs of being important (author is sometimes the "hero" type).
- Revenge: Fires set in retaliation for real or perceived injustice or wrong. Revenge can be further classified under sub-groups as:

Personal revenge: use of fire to retaliate for a one-to one or personal grievance, argument, fight, personal affront or any of infinite arrays of events perceived by the offender to warrant retaliation.

– Societal retaliation: use of fire in revenge against the society that the author perceives has wronged him.
– Institutional: fire against institutions or use of fire to settle grievances with the institution and to intimidate those associated with the institution.
– Group retaliation: fire as expression of anger towards the group or its members rather than anger at a specific individual within the group.
– Intimidation.

- Crime concealment: fire set to hide or conceal the primary crime activity: murder, suicide, breaking and entering, embezzlement, larceny, destroying records.
- Profit: profit from fire setting, either directly for monetary gain or from a goal other than money: fraud, insurance, liquidate property, dissolve business, inventory, employment, parcel clearance, competition.
- Extremist: fire set to further social, political or religious causes: terrorism, discrimination, riots/civil disturbance.

Douglas classification, with minor modifications, seems applicable to forest fires in different countries and covers a wide specter of situations, to which it gives a plausible interpretation. Understanding of the typology of arsonists, particularly

typological classification based on motivations, may actually enhance investigative efforts and provide a focus for intervention attempts.

Literature offers other examples of motivation classification. For instance, FAO (De Meo 1986) identified causes external and internal to the forestry sector. Among the former, there is voluntary, direct, conscious intervention, dictated by needs connected with agricultural and grazing practices, hunting, land use and conflicting interests. Involuntary intervention external to the forestry sector comprises: farming and agricultural activities without cautionary measures, recreational activities and the increased urban pressure in general. Among the causes internal to the forestry sector are the increasing marginality of forest resources, a widespread disregard for forest preservation and the outbreak of fires connected with job creation.

Very similar is one of the motivation classification formerly adopted and described in the 80s by the Spanish State Environment and Forest Policy Office (Dirección General de Medio Natural y Política Forestal, former ICONA) (Vélez 2000) distinguishing:

- Fires from which the starter hopes to benefit.
- Fires from which the starter assumes he will not draw tangible benefit.
- Fires caused for political reasons.
- Fires provoked by socio-economic reasons.

The official classification of causes and motivation used in the fire reports in Spain can be observed in Table 11.2. In this case it is showed the fire number and percentage registered during a 25 year period (1980–2004), because is one of the best and longest fire causes statistics in Europe. The list contains 41 different motives grouped in five general causes (lightning, negligent and accidental, deliberate, unknown and reproduced fire). As it can be appreciated, most fires are intentional, responsible for over half the fires (53.5%). Fires caused by negligence or accidents reaches 16.5% and 25% remains unknown. Only a small percentage of 4.6% is due to lighting or reproduced fires. Although the number of unknown cause fires in Spain remains high, its percentage has decreased significantly (almost by a half) from over 40% during the 80s to under 20% in the late 90s. Figure 11.1 shows the trend of unknown cause fires. In general, this improvement is undoubtedly the result of an increase interest and effort in the last years to overcome this shortage.

Spanish fire statistics were not fully satisfactory, not only due to the large number of unknown fires, but also because intentional fires were not separated between crime motivated fires and those related to traditional customs in the uses of fire. Consequently, in order to improve the information gathered a fire motivation section with 23 types was included in fire reports since 1989 (CLIF 1997a, b). In Fig. 11.1 it is observed that the increase of intentionality in Spain at the beginning of 90s is coincident with a great decreasing of unknown causes.

Gradually, the inclusion of intentional motivations in the Spanish fire database is becoming more general, although the process to gain general acceptance is slow, as it requires a greater commitment of the person acquiring the data and to apply specific investigation techniques (Vélez 2000). In 1989 in only 8% of fires

**Table 11.2** Number of fires in Spain for the period 1980–2004 classified by causes and motivations according to Fire Statistical Forms

| Cause or motivation | Num. | % |
|---|---|---|
| Lightning | 14.453 | 3.83 |
| Negligence, carelessness and accidental causes (total) | 62,084 | 16.47 |
| Agricultural burning to eliminate stubble, pruning remains, field margins, irrigation channel borders, weeds, etc. | 13,423 | 3.56 |
| Shrubland and herbaceous burning to create and maintain pastures | 9,060 | 2.40 |
| Forestry works | 4,813 | 1.28 |
| Bonfires | 3,319 | 0.88 |
| Smokers | 6,154 | 1.63 |
| Rubbish burning | 4,217 | 1.12 |
| Rubbish tip escapes | 1,257 | 0.33 |
| Burning shrubland close to buildings or for cleaning tracks, paths, etc. | 652 | 0.17 |
| Railway lines | 1,573 | 0.42 |
| Power lines | 2,708 | 0.72 |
| Engines and machines (combine harvesters, tractors, vehicles accidents, etc.) | 2,870 | 0.76 |
| Military manoeuvres | 322 | 0.09 |
| Other (apiculture, fireworks, balloons, children playing, burning of housing remains, etc.) | 11,716 | 3.11 |
| Deliberate or intentional (total) | 201,612 | 53.47 |
| Unknown intentional motivation | 124,211 | 32.94 |
| Intentional agricultural and shrubland burning | 26,344 | 6.99 |
| Intentional burning to create grazing | 23,495 | 6.23 |
| Revenges | 1,345 | 0.36 |
| To frighten off vermin or harmful animals | 1,174 | 0.31 |
| To facilitate hunting | 2,736 | 0.73 |
| Protests against game preserve | 242 | 0.06 |
| Disputes relating forest ownership | 209 | 0.06 |
| Reprisal for reduce publics investments on wildlands | 28 | 0.01 |
| To obtain salaries in extinction and restoration | 50 | 0.01 |
| Pyromaniacs (mental illness) | 8,911 | 2.36 |
| To decrease to price of timber | 127 | 0.03 |
| To obtain the modification of the land use | 389 | 0.10 |
| Caused by political groups to provoke discontent or social alarm | 94 | 0.02 |
| Antagonism against reafforestations | 261 | 0.07 |
| Caused by delinquents to distract the Police | 91 | 0.02 |
| Refusal of the creation and presence of a Protected Natural Area | 170 | 0.05 |
| Pseudo-religious or satanic rites | 96 | 0.03 |
| Caused in order to look the extinction works | 38 | 0.01 |
| Vandalism | 1,311 | 0.35 |
| To favour the production of forest products | 50 | 0.01 |
| To force the resolution of consortiums or agreements | 20 | 0.01 |
| Resentment against expropriations | 48 | 0.01 |
| Revenges against fines | 50 | 0.01 |
| Other intentional motivations (non specified) | 10,122 | 2.68 |
| Unknown cause | 96,052 | 25.47 |
| Reproduced fire | 2,860 | 0.76 |
| Total fires (1980–2004) | 377,061 | 100 |

Source: Spanish Fire Report Database. Defense Service Against Forest Fires. State Environment and Forest Policy Office. Spanish Ministry of Environment, Marine and Rural Areas.

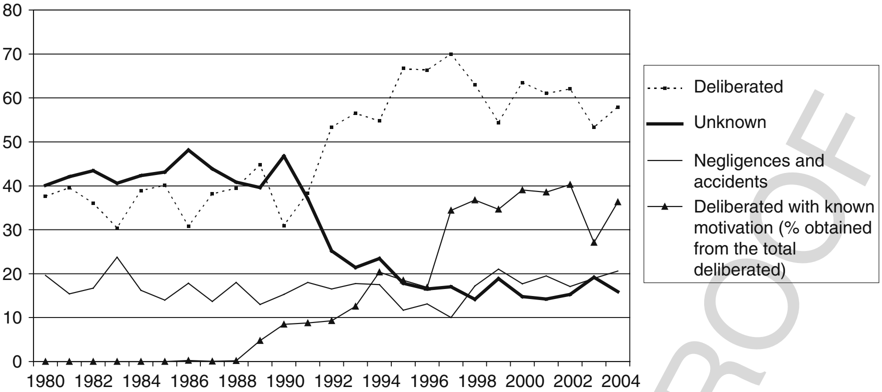



**Fig. 11.1** Temporal trends for main fire causes in Spain (1980-2004). Source: Forest Fires Service. State Environment and Forest Policy Office. Spanish Ministry of Environments, Marine and Rural Areas.

classified as intentional, the likely motivation was identified. However, as Fig. 11.1 shows, year after year this information has been increasingly included to a point in which, since 1997, the specific motivation is registered approximately in 35 to 40% of intentional fires.

As we can observe in Table 11.3, regardless the improvements achieved during last years, the causal statistic is still globally deficient and imprecise, because 65% of fires are classified either like "unknown" or using an indeterminate "intentional" or "negligent" label, without specifying a precise motivation.

The most important known human causes in Spain are the agricultural burning and the shrubland and herbaceous burning to create, maintain or re-growth pastures. The objective of the agricultural burning is to eliminate stubble, pruning remains, field margins, irrigation channel borders, weeds, shrublands in paths, etc. Both types of causes represent the 19% of fires. However, its importance could be far greater if we consider the high percentage of unknown causes. It could be estimated to fluctuate between 45 to 50% (Martínez et al. 2004).

These agricultural and grazing burnings may be negligent or intentional, depending on whether there is someone responsible of taking adequate precautions to keep the fire under control (Vélez 2000). An intentional burning is categorised as such when the site is abandoned before the fire is completely extinguished and the task is finished, and is left burning. However it will be negligence when, for some reason beyond its control, fire escapes and spreads on wildland areas. In most cases, the principal aim of these burnings is functional and economic, that is, they are not started for destructive or criminal purposes.

The remainder most important causes (according to Table 11.3) are negligence or accidents produced by smokers, forestry works, rubbish burnings, bonfires, engines and machines or electric lines (6.4%). Other noteworthy intentional motivations are pyromania (2.4%) or to facilitate hunting (0.73%).

**Table 11.3** Ranking of the 15 most important fire causes and motivations in Spain (1980–2004)

| | Cause or motivation | Num. | % |
|---|---|---|---|
| 1 | Intentional motivation unknown or non specified in fire reports | 134,333 | 35.63 |
| 2 | Unknown cause | 96,052 | 25.47 |
| 3 | Agricultural burning (both by negligence or deliberated) | 39,767 | 10.55 |
| 4 | Burning to create and maintain pastures (both by negligence or deliberated) | 32,555 | 8.63 |
| 5 | Lightning | 14,453 | 3.83 |
| 6 | Negligence causes unknown or non specified in fire reports | 11,716 | 3.11 |
| 7 | Pyromaniacs (mental illness) | 8,911 | 2.36 |
| 8 | Smokers | 6,154 | 1.63 |
| 9 | Forestry Works | 4,813 | 1.28 |
| 10 | Rubbish burning | 4,217 | 1.12 |
| 11 | Bonfires | 3,319 | 0.88 |
| 12 | Engines and machines (combine harvesters, tractors, vehicles accidents, etc.) | 2,870 | 0.76 |
| 13 | Reproduced fire | 2,860 | 0.76 |
| 14 | To facilitate hunting | 2,736 | 0.73 |
| 15 | Power lines | 2,708 | 0.72 |

Source: Forest Fires Service. State Environment and Forest Policy Office. Spanish Ministry of Environment, Marine and Rural Areas

Very similar to the Spanish one is the motivation classification adopted in Italy by CFS (Corpo Forestale dello Stato, State Forestry Department), a national police agency responsible for protecting Italy′s natural resources, the environment, countryside and ecosystems, whose most well-known protection duty is fighting wildfires. The official classification currently adopted by CFS for forest fire statistics is a list of 43 possible motives divided into five groups (natural, accidental, negligent, deliberate, doubtful or unknown) each one identified by a four-digit identification code (MIPAAF-CFS 2002). Voluntary fires are divided in two sub-groups: fires from which the starter hopes to benefit and fires from which the starter assumes he will not draw tangible benefit. For each fire event the statistic form must contain the code of the presumed or ascertained cause. A detailed statistic report on a regional basis is published annually by Corpo Forestale dello Stato.

In Italy, voluntary fires are generally considered as a symptom of problems linked to a complex series of socio-economic circumstances: the depopulation of vast areas, the abandonment of agriculture, the distribution of new settlements in rural settings, the diffusion of transportation infrastructures, the burgeoning of interests which often conflict with the conservation of natural resources etc. (Leone 2000). In 2007, unprecedented waves of fire interested the country: 10,639 fires, affecting about 228,000 ha, of which 117,000 were wooded land. Fires were accounted as voluntary for 65.5%, 31.1% of them being considered connected with profit seeking. Involuntary fires accounted for 42.2%, mainly provoked by negligent agricultural practices. The percentage of fires of unknown origin dropped from 39.2% (1999) to 19.8% probably thanks to an increase in the accuracy of data

recording and a consequence of substantial resources put into improving investigation skills and training firefighters to recognize the causes of fires. Anyhow, the assessment of cause is usually in the opinion of the reporting officer filling the fire statistic form and secure determinations are made in a minority of cases, as in every country, only when culprits are brought to justice.

## 11.4 The Delphi Technique in Human-Fire Cause Investigation

As in the case of Spain, in the majority of fire events reported in Mediterranean areas motivation remains unsolved. However, there is an ongoing need to improve the knowledge of this point, which is a precondition for the implementation of suitable solutions. A promising technique for improving the abovementioned difficulty is the Delphi technique, a decision-making method named after the famous oracle of Delphi. The Delphi technique was originally developed in the 50s by Olaf Helmer and Norman Dalkey, scientists at the Rand Corporation, as an iterative process for forecasting likelihood that certain events will occur. It is a study method designed as a means of scientific prediction (Baughman 1989). Distinguishing features of the Delphi technique are: anonymity, iteration with controlled feedback, statistical group response and expert input.

The Delphi technique uses a panel of carefully selected experts who answer a series of questions through either correspondence or face-to-face discussion. The accuracy of the prediction, of course, depends on the competence, experience, objectivity and perception of the discerning judge. Each round of questioning is followed by feedback on the preceding round of replies, usually presented anonymously. The experts are encouraged to revise their earlier answers in light of the replies of other members of the group.

The Delphi technique generally includes several steps:

- the specification of a topic or subject to be investigated;
- the construction of an ad hoc questionnaire for data collection;
- the selection of a panel of experts on the topic being investigated;
- the weighting of the opinions of the experts by means of the questionnaire;
- the summary of the data resulting from the initial measurement;
- the communication of the results of the initial weighting of opinions as feedback to all the respondents;
- a re-evaluation of the opinions of the respondents;
- an analysis, interpretation, and presentation of the data and the writing of a final report.

While the Delphi is considered a forecasting procedure due to its significant use in that area, there is a variety of other application areas, among which we find developing causal relationships in complex economic or social phenomena and distinguishing and clarifying real and perceived human motives (Linstone and Turoff 2002); this latter feature correctly fits the region where fires are occurring.

Delphi method gave interesting results in different study-cases in the South of Italy within a high fire incidence area (De las Heras et al. 2007; Lovreglio et al. 2008). In this study, experts in the field of forest fires were found through the natural resources of professionals working for governmental and/or non-governmental organizations, namely the foresters belonging to Corpo Forestale dello Stato. As already mentioned, their most well-known protection duty is fighting wildfires. Foresters in Forest Stations have, in addition, the duty of working out forest fire statistics. For this reason, they must be considered deeply knowledgeable and broadly experienced in the subject matter.

Structured questioning was achieved through the use of ad hoc questionnaires where the 43 possible official motives of fire in Italy, divided into five groups (natural, accidental, negligent, deliberate, doubtful or unknown) were reported. The use of the questionnaire allowed for anonymous responses, giving the group members the freedom to express their opinions without feeling pressured by the wider group or dominant members. Experts were given the form, reporting the list of motives and their four digit identification codes, and asked to identify ("voting") the eight most important and frequent motives and, successively, to rank them ("score") in order of decreasing importance.

Instead of the usual summary of the overwhelming majority of causes as arsonist or unknown, the experts in the above mentioned research attribute the majority of fire ignitions to cultural behaviors or social tensions and give answers which appear to be rather homogeneous and convergent despite the difference of study areas. Respondents actually moved from the so called "conspiracy logic" that looks towards delinquents to a deeper socio-economic causal analysis (Martín et al. 2002) confirming that the choice of experts is the crucial step of the method.

In the first rank order, i.e. scored 1, the most relevant group is referred to agricultural use of fire, whereas a less important group of motives refers to deliberate fire setting. Enlarging the comments to the first four ranks, motives connected with negligent fires were referred to careless use of agricultural fires. The most frequent motive was stubble burning, i.e. systematic burning for the purpose of the preparation of the agricultural terrain for new sowing and the elimination of residue or thicket. This is a traditional operation on cereal growing lands (FAO 2005), which are the most common land-use type in the study areas, which exhibit a marked and prolonged summer drought. The principal aim of agricultural burnings is functional, that is, they are not started simply for destructive purposes. In fact, these burnings are legally authorized so long as they comply with certain conditions, but they turn illegal through failure to comply with preventive measures laid down by the law. Respondents give minor emphasis, in rank ordering, to the obvious and rather banal motive of cigarettes carelessly discarded, which is, on the contrary, one of the most recurrent in some official surveys.

Taking a look at deliberate fires, the most relevant motives in the four study areas were closely related to labour conflicts. The motives confirm the importance and presence of the so called fire industry (Leone and Vita 1892; Leone et al. 1988, Leone and Saracino 1990; Leone 1997) i.e. voluntary fires lit by seasonal workers as an instrument for forcing/maintaining employment and/or creating new

job opportunities (CFS 1992); clearly it is a case of fire as a means of subsistence, intentionally set by fire-fighters as a way to maintain their job and increase their revenue (WWF 1993). Deliberate fires of this kind have a correlation with the level of income (Leone and Vita 1892): the lower the level of income, the higher the number of provoked fires (Vélez 1986). The motive referring to conflict with authorities, which are observed only in some restricted areas (for instance the National Park of Gargano, in Apulia), could be interpreted as a sort of reaction against land use restrictions in protected areas, which sometimes explode in very violent ways. Confrontation can occur, of which the forest fire is a symptom (FAO 2005), as an unorthodox way of affirming rights of use. Conflicts with Public Administration could be interpreted in a similar way.

The motives which refer to ownership conflicts are ranked relatively low in terms of importance and could be interpreted in some areas, such as the Gargano National Park, as conflicts between shifting shepherds who are not owners of grazing land but only landless occupants, and stable rural dwellers, indicating a social and intrinsic problem in the sheep-farming system (Leone et al. 2002; Leone et al. 2003; Leone and Lovreglio 2003). The popular and abused motive which usually refers to fire used as a tool to convert rural land into urban land is absent in the results.

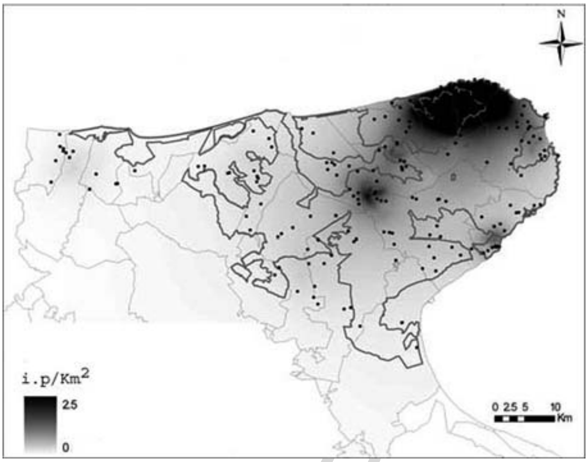
A special remark must be made for pyromaniacs, a motive which received rather high frequency but ranked low in terms of importance. The term pyromaniac is largely misused as a synonym of arsonist, not only in Italy but also in other countries (APAS 2003; Dolzreuss and Franco 2005). Psychologists agree that pyromaniacs – people with a mental illness resulting in an uncontrollable urge to start fires – account for only a small minority of arson. Doley (in Willis 2004) cites a number of studies showing that the reported incidence of pyromania is now very low. Despite this, and despite its existence as a psychiatric diagnosis, it seems likely that there are few true pyromaniacs or even that the diagnostic category is really a valid one.

Its high scoring by the panel could be thus interpreted as a case of being misinformed or lacking information, even by the experts and is a further confirmation of diffuse, common improper use of the term.

It must be highlighted that when the percentage of unknown causes is high, as in some regions or provinces in Italy, Delphi method and the exploitation of experts' knowledge remain the sole possibility to give a plausible explanation to the phenomenon. Delphi method is, in addition, an excellent integration to other tools of geographical analysis, such as the kernel density maps, since it permits to give a plausible explanation to the geographical pattern of ignition points which often exhibits anomalous concentrations.

In a recent Delphi survey of motivations for the Gargano National Park, in Apulia (Italy), carried out in the frame of the Fire Control and Prevention Plan for 2009–2011, the experts' panel resisted mundane explanations of the phenomenon linked to pyromaniacs and cigarettes carelessly discarded. They clearly pinpointed that fire are related, among other motivations, to illegal land use changes (from natural pine forests to olive crops) confirming the result of a previous research (Leone et al. 2002; Amatulli et al. 2005). In Fig. 11.2 the kernel density map of the area is

**Fig. 11.2** Kernal density map (10 i.p.km$^2$) for the Gargano National Park.




presented, showing a clear concentration of fires in the inner North-Eastern part of the promontory.

Figure 11.3 is a true color orthophoto detail of the area most severely affected by fire along years (inner territory of Peschici), showing a series of irregular clear parcels. Those are mainly fire scars which still maintain their shape but which, in their majority, turned into very recent olive crops. Figure 11.4 is a typical example of land use change. Fire easily permits to change scarcely rentable pine stands into more profitable olive crops, which take advantage from the Protected Designation of Origin (PDO) of extra virgin olive oil produced in the area.

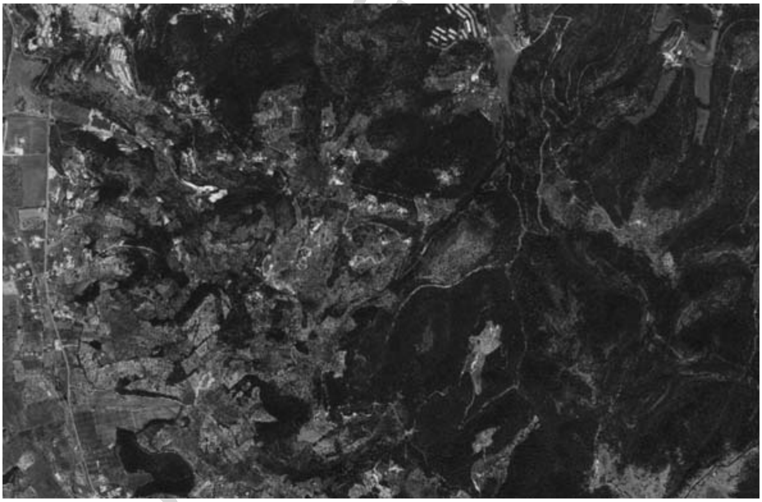


**Fig. 11.3** Orthophoto of the inner part of the territory of Peschici (Gargano National Park).

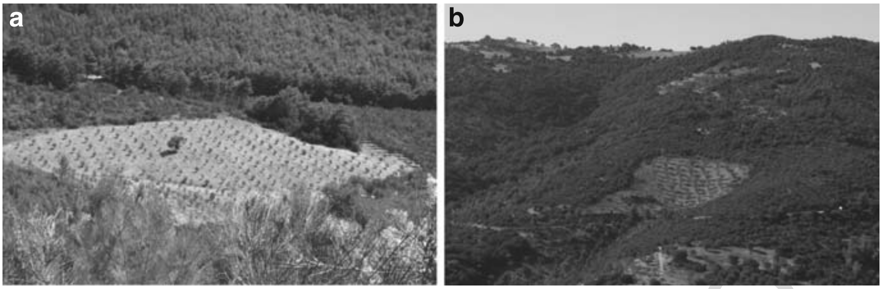



**Fig. 11.4** Examples of land-use changes prompted by fire in the Gargano National Park.

## 11.5 Human Factors in Fire Risk Estimation

It is evident that humans play an important role in fire ignition, since most fires are, directly or indirectly, caused by human activities. On the other hand, humans must face also the main consequences of wildland fires. Therefore, the human factor has a critical importance in all phases of fire management. In spite of that, there is still a long way to go in terms of prediction and modelling of fire risk of human origin and also in the integration of human and natural factors in a comprehensive risk scheme, which also include an adequate estimation of vulnerability associated to humans.

Fire risk assessment is routinely performed in most developed countries that are affected by forest fires in order to establish fire prevention actions. Estimating forest fire risk involves identifying the potentially contributing variables and integrating them into a mathematical expression, i.e. an index. This index, therefore, quantifies and indicates the level of risk. A literature review of forest fire risk methods shows how different definitions and also different approaches are used for the evaluation of fire risk (FAO 1986; NWCG 2006; Bachmann and Allgöwer 2000). Chuvieco et al. (2004c, 2007) propose that an integrated assessment of fire risk should consider both fire ignition probability, as well as the assessment of potential damages (vulnerability of the affected areas). Additionally, most operational fire risk systems are focused on physical factors: weather data and fuel status mainly, but, especially in Europe, a growing concern about the role of human activities in fire ignition and propagation is widely recognized (Kalabokidis et al. 2002; Martínez et al. 2004). Therefore, any risk assessment system should also include the consideration of socio-economic causes of fire, as well as the vulnerability associated to human beings (life, properties and values).

Human risk of ignition may be defined as the probability of a fire occurring as a result of the human presence and activity, either directly or indirectly. The evaluation of human activity as an agent of ignition is a complex task, one reason being the lack of accurate information about the number of people present in the forest, their activities and their use of fire (Vega-García et al. 1993). In fact, the temporal and daily data needed to evaluate the human factor in fire risk is not generally available, in contrast to other risk variables such as temperature or relative humidity which

are more easily obtained and updated. Moreover, human activities are one of the most dynamic elements of space and, on certain occasions, do not tend to follow specific spatial patterns, or rather these are more difficult to determine, as in the case of pyromania or specific deliberate motivations. Due to obvious difficulties, investigators and the responsible fire-fighting bodies have frequently adopted two solutions in this respect; either leave the human risk factor out of their prediction models or deal with it only very marginally; or obtain some indirect estimators of human risk activity, which are generally structural in nature and refer to the most permanent features of the land and population.

In spite of the difficulties, many human risk factors can be directly or indirectly measured through spatially represented variables, such as recreational activities and burning of shrub land for pastures, which tend to be associated to particular areas whose location can be mapped. Geographic Information Systems (GIS) are appropriate tools to create, transform, combine and integrate variables related to fire risk, taking into account geographical and analytical relationships in order to discriminate areas where risk factors are most severe (Salas and Chuvieco 1994, 1996; Castro and Chuvieco 1998; Gouma and Chronopoulou-Sereli 1998; Pew and Larsen 2001; Cardille et al. 2001). This integration is done using GIS after building a fire occurrence prediction model. Many of these models have been based on the abundant geographic data generated as GIS evolved, focusing on where historical datasets of fires were located in relation to roads, trails, towns, vegetation, rivers, topography (elevation, slope, aspect), power lines, railways, industries, forestry operation sites and many more geographic variables (Chou et al. 1990). Usually, they found valid relations over long periods of time for reduced geographic units. However, few attempts have been made to produce human risk models that could be used at national and regional scales due to the difficulty to obtain digital data in an accessible format which could be considered up to date and homogeneous for a whole country or a region. Frequently the data necessary to measure a specific factor does not exist for all or any of the study units. In other occasions the effort to obtain it is extremely high.

The probability of fire occurrence varies in time and space depending on different risk factors. Because of that, the first predictive models developed in this context were based on binomial and Poisson distributions suitable for rare events (Cunningham and Martell 1973). However, the most widely used statistical method to predict the probability of ignition is logistic regression (Martell et al. 1987; Lorenzo and Pérez 1995). This technique quantifies the relationship between a dichotomous response variable (i.e. the presence or absence of a fire ignition) and a set of explanatory variables. Logistic regression has been used by several authors (alone or in combination with other methods) to obtain predictive models of fire ignition both at local (Vasconcelos et al. 2001; Vega-García et al. 1995; Lin 1999; Pew and Larsen 2001) and regional scales (Chuvieco et al. 1999; Martínez et al. 2004). More recently Kalabokidis et al. (2007) studied the spatial distribution of long-term fire patterns versus physical and anthropogenic elements that determine wildfire dynamics in Greece using logistic regression and correspondence analysis. Martínez et al. (2009) identified human factors associated with high forest fire risk in Spain using logistic

regression and analyzed the spatial distribution of fire occurrence at municipality level. Prasad et al. (2008) used also logistic regression to estimate the probability of fire occurrence as a function of topography, vegetation, climate as well as anthropogenic and accessibility factors in the Deccan Plateau (India). Vilar del Hoyo et al. (2008) obtained human fire risk models in Madrid and Valencia regions (Spain) through logistic regression from a set of 31 socioeconomic variables. Explanatory variables where spatially mapped from cartographic and statistical sources using GIS tools at 1 km$^2$ UTM. This spatial unit was selected for the study as it was considered by fire experts as being the most appropriated for fire management at the regional level.

Along with logistic regression other statistical methods such as linear regression, classification regression trees, neural networks or Bayesian probability have also been used in fire risk mapping to generate local risk models. Chao-Chin (2002) applied multivariate regression to fire occurrence prediction in Taiwan. The model integrated biophysical and human behavioral components related to fire risk. Robin et al. (2006) predicted fire ignition probability in the Alpes-Maritimes (France) from distance to roads and human settlements using an intuitive approach combined with a non-linear regression and logit regression. Amatulli et al. (2006, 2007) tested the capability of Classification and Regression Trees (CART) analysis to assess long-term fire risk at local scale in the Southest of Italy and Aragón (Spain) respectively. The predictor data included physical and anthropogenic variables. Amatulli and Camia (2007) compared Classification and Regression Tree (CART) and Multivariate Adaptative Regression Splines (MARS) techniques for predicting fire occurrence in the Arno River Basin (Italy). They used road network, topographic variables and population data along with fire ignition points to build the models. Syphard et al. (2007) examined the influence of fires in California by relating contemporary and historic fire data with both human and biophysical variables using bivariate and multiple regression methods. Yang et al. (2007) used a spatial point process modeling approach to study the effects of land cover, topography, roads, municipalities, ownership and population density on fire occurrence in Missouri Ozark Highland forests (US). They used the Akaike Information Criterion (AIC) to select an appropriate inhomogeneous Poisson process model to fit the data. Vega-García (2007) developed neural network models for daily fire prediction in Catalonia (Spain) using geographic (human and biophysical) and meteorological variables. Vilar del Hoyo et al. (2007) proposed a comparison of human fire risk models obtained through logistic regression, classification trees and neural networks in Madrid and Huelva regions (Spain). Koutsias et al. (2004) tried to explain long-term wildland fire occurrence patterns in southern Europe comparing classical ordinary least squares (OLS) linear regression with geographically weighted regression (GWR). Romero-Calcerrada et al. (2008) through a Bayesian method (weights of evidence) examined the causal factors of wildfires in Madrid region (Spain), using socioeconomic and spatial variables.

Even though a wide range of research works has been found in the literature that try to explain and/or predict fire occurrence related with human activity, most of these models haven't been implemented yet in current operational

fire risk systems. The Canadian Forest Fire Danger Rating System (CFFDRS, http://fire.cfs.nrcan.gc.ca/research/environment/cffdrs/cffdrs_e.htm), for example, is still in the process of including the Canadian Forest Fire Occurrence Prediction (FOP) subsystem (currently under consideration for formal development) which is envisioned as a national framework including models for both lightning- and human-caused fires. In Europe, the Joint Research Centre (JRC) operates the European Forest Fires Information System (EFFIS) which is meant to support forest fire protection through information at the European level. EFFIS has been developed and is implemented by JRC also through collaboration with the relevant services of the Member States, and under the coordination of EC-DG ENV Civil Protection Unit. EFFIS includes a fire risk index, composed by a long-term index and a short-term or dynamic index (Salas and Cocero 2004). The dynamic index (Fire Danger Forecast module) is calculated using the Canadian Fire Weather Index (FWI) as the method to assess the fire danger level in a harmonized way throughout Europe. On the other hand, the long-term index was proposed to be composed by the Fire Probability Index and the Vulnerability Index (Salas and Cocero 2004). Sebastián et al. (2001) developed the former that would estimate the fire probability occurrence considering available fuel, topographic and socioeconomic variables. This index was calculated for European southern countries and at 1 km$^2$ cell grid resolution, but it was not implemented in the operational system.

There is still a long way to go in terms of prediction and modeling of fire risk of human origin and also in the integration of human and natural factors in a comprehensive operational scheme. However, in the last years, some research projects have made a great effort to investigate the mechanisms behind human fire occurrence and derive prediction models for human caused fires, which would be operationally integrated into a fire risk assessment system for fire prevention and management at different spatial scales. In the United States, the WALTER project (available at http://walter.arizona.edu/) proposes the Fire-Climate-Society Strategic Fire Model, which combines biophysical and social science with advanced geospatial, decision support, and interactive web technologies to build integrated decision-support tools for use by experts and by the public. In the society component of WALTER, data sets and GIS layers providing information about population density, land use patterns, the location of trails and roads, perceived values, and species habitat richness are used to incorporate human factors into the model. Five factors are taken into account for the model: recreation value (how people value an area for recreational use), species habitat richness (how people value an area for the richness of the flora and fauna found there), property value (how valuable is property located in an area), perceived landscape value (the value humans put on the landscape) and human factors of fire ignition (how frequently human-caused fires typically occur in the area). Through a logistic regression analysis it was revealed that human ignitions were spatially associated with the human factors. These factors include proximity to roads, location of campgrounds and picnic areas, proximity to urban areas, non-forested vegetation layers and urban-wildland border complexity.

In Europe the FIREMAP project proposes an integrated fire risk index at a regional scale that takes into fire danger and also includes explicitly the

(b) (d)

(a) (c)

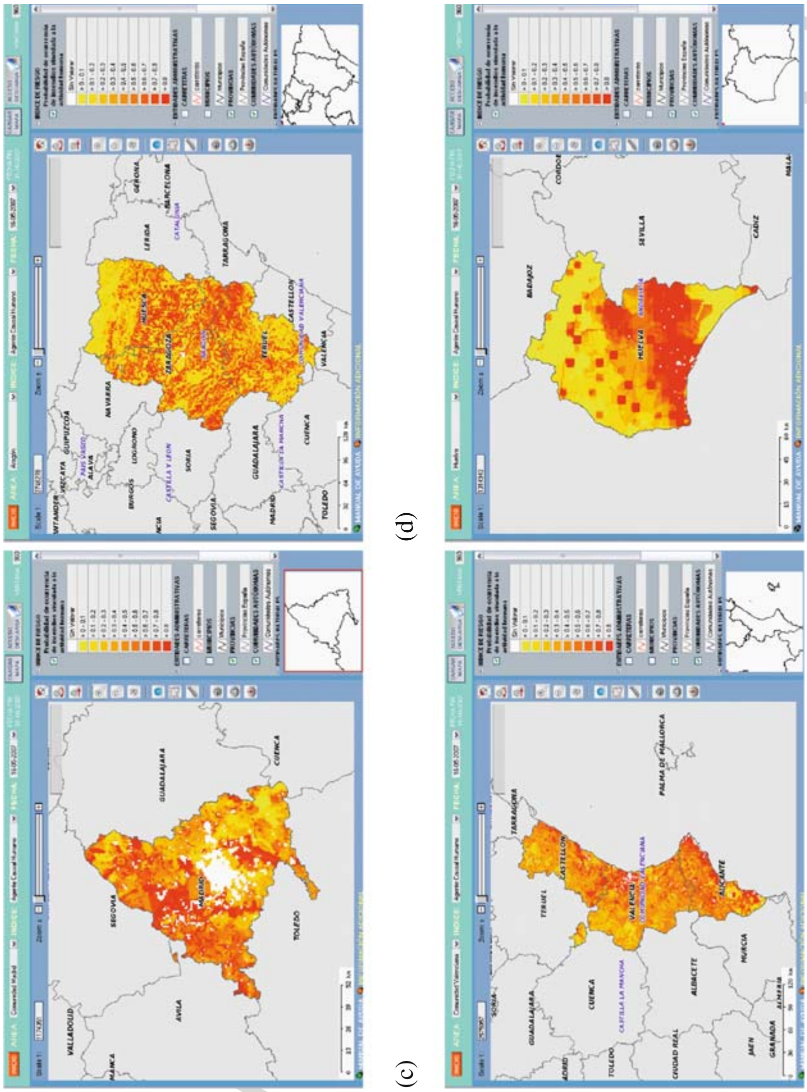


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**Fig. 11.5** Human fire risk probability map as included in the FIREMAP map sever. Madrid region (**a**), Aragon region (**b**), C.Valenciana region (**c**), Huelva region (**d**). http://www.geogra.uah.es:8080/cartofire*

*For colour version of this figure, please refer Colour Plate Section.

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vulnerability aspects of fire which were neglected in previous approaches (Chuvieco et al. 2007). The fire danger index considers the potential that a fire ignites or propagates. The two main sources of ignition were considered: human and natural. In addition to ignition sources, the moisture status of plants was also considered. The propagation component of fire danger is associated to the potential of fire spreading, as a result of fuel amount and continuity, plus favorable terrain and weather conditions (mainly wind speed). The vulnerability component which refers to the potential damage caused by the fire includes three aspects: socio-economic values (properties, wood resources, recreational importance, carbon stocks, etc.), degradation potential (soil and vegetation conditions), and landscape value (uniqueness, conservation status, etc.). The human fire ignition component includes variables related to land uses and socioeconomic factors. Forward Stepwise Logistic Regression analysis was used to estimate the probability of occurrence from socioeconomic explanatory variables (Vilar del Hoyo et al. 2008) derived from cartographic or statistical sources at 1 km$^2$ grid cell resolution: wildland-urban interface, forest-agriculture interface, recreational areas, variation of the population (socioeconomic changes factor), buffer of roads, buffer of railways (negligence or accidents factor), natural protected areas, unemployment rate (conflicts that can break the beginning of deliberated fires factor), fire watch towers (fire prevention factor), cattle charge, agricultural machinery presence (traditional activities in rural areas factor). After applying different statistical tests to avoid multicolinearity problems, a spatial explicit human fire risk probability model was obtained for the study regions as illustrated in Fig. 11.5. All the components of the FIREMAP fire risk index were integrated into a web-mapping service system available for fire managers.

## 11.6 Epilogue

A more thorough knowledge on the reasons lying behind fire occurrence is extremely helpful to appropriately plan prevention actions in order to reduce their incidence. By understanding more about why people start fires we can, in addition, find ways of reducing the impacts of deliberate firefighting (Willis 2004). Knowing more about the motives underlying wildfire arson and ways of managing and treating its perpetrators, may give us a greater chance of finding the culprits, bringing them to justice and trying to stop them from lighting fires in the future.

Spatial analysis tools such as the Geographic Information Systems are a valuable help to reach a better and more logical interpretation of this complex phenomenon. A better understanding of spatial and temporal patterns of wildland fire occurrence data and/or associated explanatory geographical variables is a crucial part of fire management activities as pre-fire planning requires objective tools to monitor when and where but also why a fire is more prone to occur.

# Chapter 11

| Q. No. | Query |
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| AQ2 | Au: Please specify whether “Lovreglio et al. 2008” is “2008a” or “2008b.” |
| AQ3 | Au: Please specify whether “FAO 2005” is “2005a” or “2005b.” |
| AQ4 | Au: Please specify whether “FAO 2005” is “2005a” or “2005b”. |
| AQ5 | Au: "NWCG 2006" is not listed in the reference list. Please provide. |
| AQ6 | Au: Please specify whether “Chuvieco et al. 2007” is “2007a” or “2007b”. |
| AQ7 | Au: "Amatulli et al. 2006" is not listed in the reference list. Please provide. |
| AQ8 | Au: "Vega-García 2007" is not listed in the reference list. Please provide. |
| AQ9 | Au: Please specify whether “Chuvieco et al. 2007” is “2007a” or “2007b”. |

# Chapter 12
# Forest Fire Emissions and Air Pollution in Southern Europe

**Ana I. Miranda, Carlos Borrego, Helena Martins, Vera Martins, Jorge H. Amorim, Joana Valente, and Anabela Carvalho**

**Abstract** Forest fires are one of the most impressive forces of nature. Their disturbing effects include, among many others, the emission of large amounts of gases and particles to the atmosphere, with significant impacts on air quality and human health. The work here presented summarizes the current state of research in what respects to the atmospheric emissions of forest fires and their relation with air quality. An overview of the current emission models is presented, including a collection of emission factors suitable for application to south European forest fires. Emission measurement techniques, as well as air quality measurements, are presented under the framework of Lousã 2004 field fire experiments. The extreme fire events that took place in the summer of 2003 in southern Europe are illustrated with two case studies for Portugal. Two air quality modelling systems were applied, LOTOS-EUROS and AIRFIRE, revealing the severe degradation of air quality due to forest fires, namely in what concerns to particulate matter and ozone levels. The need to integrate air quality policies in forest management in order to reduce the number of air pollution episodes besides the risk of unwanted fires is a clear outcome of this chapter

## 12.1 Introduction

A forest fire is a large-scale natural combustion process consuming various types, sizes and ages of botanical specimen growing outdoors in a defined geographical area. Although wildland fires are an integrant part of ecosystems management and are essential to maintain functional ecosystems (Sandberg et al. 2002) their dimensions can give rise to disastrous results. Due to the frequency of occurrence and the magnitude of effects on the environment, health, economy and security, forest fires have increasingly become a major subject of concern for decision-makers, firefight-

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ers, researchers and citizens in general. Among their consequences, the emission of various environmentally significant gases and solid particulate matter to the atmosphere interfere with local, regional and global phenomena in the biosphere.

Smoke from forest fires contains important amounts of carbon dioxide ($CO_2$), carbon monoxide (CO), methane ($CH_4$), nitrogen oxides ($NO_x$), ammonia ($NH_3$), particulate matter (PM) (that is usually referred in terms of particles with a mean equivalent diameter less than 2.5 μm, or $PM_{2.5}$, and particles with a mean equivalent diameter less than 10 μm, or $PM_{10}$), non-methane hydrocarbons (NMHC) and other chemical compounds. These emitted compounds can cause serious consequences to local and regional air quality by reducing visibility, contributing to smog and impairing air quality in general and thus threatening human health and ecosystems. CO, $CH_4$, NMHC, and $NO_x$ are chemically active gases that strongly influence the local/regional concentrations of the major atmospheric oxidants (ozone ($O_3$) and the hydroxyl radical OH), and high levels of tropospheric ozone can occur at great distances from emission sources (Crutzen and Andreae 1990; Crutzen and Carmichael 1993). The production of aerosols is also very important, giving rise to local pollution, and affecting the radiation budget of the Earth and, hence, impacting global climate. Globally, fires are a significant contributor of $CO_2$ and other greenhouse gases to the atmosphere. Fires account for approximately one fifth of the total global emission of $CO_2$ (Sandberg et al. 2002). Even taking into account the notion that fires in temperate ecosystems are minor contributors compared to biomass burning in savannas, boreal and tropical forests, the contribution to total $CO_2$ equivalent emissions produced during forest fires can reach 7% when the annual area burned exceeds 100,000 ha (Miranda et al. 1994a).

Moreover, severe air pollution episodes caused by fires in Amazonia (Brazil), Indonesia and Philippines in 1997/98 and, more recently, in Australia, Russia and United States of America, have drawn worldwide attention to the problem of air quality degradation due to forest fires. This type of smoke pollution due to forest fire events can represent an important public health issue to the affected communities and particularly for the personnel involved in firefighting operations (Brustet et al. 1991; Ward et al. 1993; Miranda et al. 1994b; Reinhardt et al. 2001; Miranda et al. 2005a; Valente et al. 2007).

Increasingly, smoke pollution due to wildland fires is considered an important health issue with major risks for the population and the environment. The World Health Organization (WHO) has even provided guidelines for forest fire episodic events to protect the public from adverse health effects (WHO 1999). This concern also applies to prescribed fires, especially in Australia and North America where this land management technique is frequently used.

The main purpose of this chapter is to provide an overview of the relation between forest fires and air pollution taking into account emissions, and pollutants dispersion and chemistry. It will be focused on the southern European region and several examples will be given to illustrate experimental and modelling case studies in Portugal.

## 12.2 Atmospheric Emissions from Forest Fires

Forest fires atmospheric emissions depend on multiple and interdependent factors like forest fuels characteristics, burning efficiency, burning phase, fire type, meteorology and geographical location:

- Fuel type and fuel load are two of the most important factors affecting fire emissions. Variations in fuel characteristics and consumption may contribute to 30% of the uncertainties in estimates of wildfires emissions (Peterson 1987; Peterson and Sandberg 1988). This is a critical factor when describing forest fuels because available fuel mass depends on the location, fuel type and time of the year.
- Burning efficiency is also a significant factor for fire emissions, which is usually defined as the ratio of carbon released as $CO_2$ to total carbon present in the fuel. For convenience, the modified combustion efficiency can also be used; meaning the ratio of carbon released as $CO_2$ by the sum of $CO_2$ and CO (Ward 1999) and is directly related to the vegetation type and its moisture content. In laboratory and field experiments, the burning efficiency can be expressed as the fraction burned related to the total biomass available.
- Emissions estimates for biomass burning distinguish different combustion phases. The duration or predominance of burning phases depends on fuel type/mixture, moisture content and atmospheric conditions. For biomass burning, the following phases can be considered: pre-ignition, flaming, smouldering and glowing. According to Lobert and Warnatz (1993) during the flaming phase, the most emitted compounds are $CO_2$ and water vapour and, in less quantity, $NO_x$, sulphur dioxide ($SO_2$), nitrogen ($N_2$) and particles with high carbon content. More oxidizes emissions are predominant as a result of higher burning efficiency. In the smouldering phase, partially oxidized or reduced emissions are predominant, namely CO and others like $CH_4$, NMHC and polycyclic aromatic hydrocarbons (PAH), $NH_3$, sulphur compounds and particles with low black carbon content. CO is the main compound emitted in this phase.
- Concerning the type of fire, heading fires have high propagation speed and fuel consumption rate, and therefore low burning efficiency and less oxidized emissions. Backing fires have low propagation speed and long residence time, and therefore high burning efficiency and more oxidized emissions.
- Meteorological parameters as air temperature, humidity, precipitation, wind direction and intensity are other factors affecting the moisture content of fine fuels and soil duff. Fuels dryness increases flammability and flame propagation speed. Atmospheric stability has also a significant role in fire behaviour in the initial combustion phases. Rain and hail are important meteorological elements to be considered in fire extinction, but can also contribute to the increase of the available biomass fuel after winter and spring.

### 12.2.1 Emissions Modelling

Emissions from forest fires can be estimated using models, e.g. FOFEM (Reinhardt et al. 1997), EPM (Sandberg and Peterson 1984), CONSUME (Ottmar et al. 2002), or EMISPREAD (Miranda et al. 2005b). They are frequently based on a methodology, which includes the emission factors, the burning efficiency, the fuel loads and the burned area. Hence, emissions can be estimated through the following simple expressions:

$$E_i = A \times B \times \beta \times FE_i \text{ or } E_i = A \times FE_i$$

in which,

A – available fuel area ($m^2$)
B – fuel load ($kg\ m^{-2}$)
β – burning efficiency (as fraction of biomass burned)
$FE_i$ – emission factor for pollutant i ($g\ kg^{-1}$ or $g\ m^{-2}$)
$E_i$ – emissions for pollutant i (g)

Emission factors are defined as mass of pollutant emitted per mass of burned fuel or per burned area. A great variety of emission factors can be found in the literature, dealing with different fire types, burning phases and fuel types. For instance, there is a significant difference between emission factors from experimental and prescribed fires compared to emission factors from wildfires. Hence the use of emission factors from controlled/prescribed fires to predict emissions in wildfires may result in great error. The determination of emission factors contributes to 16% in estimative errors for forest fire emissions (Peterson 1987; Peterson and Sandberg 1988).

Miranda (2004) presented a selection of emission factors for South-European forest fires. This review and summarizing work was further updated and expanded, taking into account more recent works and additional pollutants. Table 12.1 compiles the emission factors for the following air pollutants: $CO_2$, CO, $CH_4$, total particulate matter (TP), $PM_{2.5}$, $PM_{10}$, NMHC, $NO_x$, $NH_3$ and $SO_2$, for different type of fires and burning phases.

In the case of $CO_2$, the emission factors already integrate burning efficiency. Also, emission factors expressed as burned fuel area for southern European forest are presented in Table 12.2.

Emission ratios are other method to estimate forest fire emissions, specially used in field experiments, because they do not depend on the burned mass fuel or composition. Emission ratio for pollutant $X_i$ (RE $\{X_i\}$) is defined as the ratio of the emission of pollutant $X_i$ and the emission of other pollutant, chosen as reference. Usually, $CO_2$ is selected for the flaming phase and CO or TP for the smouldering phase, as reference pollutants.

In the European context, and according to data from the European emission inventory EMEP/CORINAIR (European Environmental Agency, 2004), forest fire emissions represent 0.2% of nitrogen dioxide ($NO_2$), 0.5% of NMHC, 1.9% of CO and 0.1% of $NH_3$. For Portugal, the contribution of forest fire emissions in 2003 to the total value equates to 14.1% of CO, 5.2% of $NO_2$, 2.7% of NMHC, 2.2% of

**Table 12.1** Averaged emission factors (g $kg^{-1}$) for South-European forest fires (Miranda et al. 2005b)

| | | Emission factors (g $kg^{-1}$) | | | | | |
|---|---|---|---|---|---|---|---|
| Pollutants | Burning phase/fire type | Herbaceous | Brushwoods | Resinous | Resinous w/brushwood under-story | Eucalyptus | Deciduous |
| $CO_2$ | F/B | 1,450 | 1,509 | 1,704 | 1,562 | 1,530 | 1,537 |
| | S/H | 1,414 | 1,426 | 1,440 | 1,421 | 1,327 | 1,293 |
| G | 1,418 | 1,477 | 1,627 | 1,487 | 1,414 | 1,393 | |
| CO | F/B | 78 | 88 | 55 | 64 | 57 | 46 |
| | S/H | 106 | 95 | 180 | 155 | 161 | 183 |
| G | 103 | 82 | 75 | 70 | 117 | 128 | |
| $CH_4$ | F/B | 3 | 3 | 1 | 2 | 3 | 2 |
| | S/H | 6 | 5 | 5 | 4 | 8 | 9 |
| G | 5 | 4 | 6 | 5 | 6 | 6 | |
| NMHC | F/B | 3 | 8 | 2 | 5 | 5 | 4 |
| | S/H | 7 | 14 | 6 | 10 | 10 | 8 |
| G | 6 | 9 | 5 | 7 | 7 | 6 | |
| TP | F/B | 20 | 36 | 11 | 25 | 19 | 13 |
| | S/H | 21 | 19 | 39 | 29 | 20 | 20 |
| G | 21 | 20 | 20 | 20 | 19 | 18 | |
| $PM_{2.5}$ | F/B | 15 | 7 | 6 | 6 | 7 | 6 |
| | S/H | 13 | 11 | 12 | 12 | 12 | 12 |
| G | 13 | 9 | 10 | 9 | 11 | 11 | |
| $PM_{10}$ | F/B | 16 | 8 | 6 | 7 | 8 | 7 |
| | S/H | 15 | 12 | 13 | 3 | 13 | 13 |
| G | 15 | 10 | 10 | 10 | 13 | 13 | |
| $NO_x$ | F/B | 6 | | 4 | 3 | 3 | |
| | S/H | 3 | | 0.7 | 1 | 1 | |
| G | 5 | 7 | 4 | 5 | 4 | 3 | |
| $SO_2$ | F/B | 1.8 | | | | | |
| | S/H | | | | | | |
| G | 1.4 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | |
| $NH_3$ | F/B | 0.1 | 0.1 | 0.4 | 0.4 | 0.4 | 0.4 |
| | S/H | 0.6 | 0.6 | 1.6 | 1.6 | 1.4 | 1.6 |
| G | 0.6 | 0.6 | 0.8 | 0.4 | 0.6 | 0.6 | |

Note: F – Flaming phase; S – Smouldering phase; G – Global fire; B – Backing fire; H – Heading fire

**Table 12.2** Emission factors expressed as burned fuel area for Mediterranean forest (Simpson, 1999)

| **Forest type** | **Emission factors (kg $ha^{-1}$)** | | | | | | |
|---|---|---|---|---|---|---|---|
| Mediterranean forest | **CO** | **$CH_4$** | **NMVOC** | **$NO_x$** | **$NH_3$** | **$N_2O$** | **$SO_2$** |
| | 1,456 | 54 | 133 | 51 | 11 | 3 | 11 |

$CH_4$, 1.3% of $NH_3$ and 0.6% of $SO_2$. These percentages were estimated using data from the national emission inventory for non-forest-fire emissions and result from the model EMISPREAD (Miranda et al. 005b), which takes into account the type of fuel and combustion phase to estimate forest fire emissions from southern Europe.

### *12.2.2 Emissions Measurement*

Atmospheric emissions from forest fires can also be measured. The burning experiments performed since 1998 in Serra da Lousã, Central Portugal, aimed to collect a large range of different but complementary experimental data, which can be used to support the development of new concepts, methods and models and to validate the existing ones within various fields of fire management (Viegas et al. 2002). These experiments also provide a particularly important opportunity to measure and analyse air pollutant concentrations during experimental field fires (Miranda and Borrego 2002).

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The experiments undertaken in 2004 are reported here in what concerns to emissions measurement. More details can be found in Borrego et al. (2005) and Valente et al. (2007). Figure 12.1 presents the location of Serra da Lousã, the burning plots, and the used mobile laboratories. Figure 12.2 shows two images of the 2004 field fire experiments. The vegetation was mainly constituted of continuous shrubs of which three dominant species were identified: *Erica umbellata*, *Ulex minor* and *Chamaespartium tridentatum.* The experimental area was divided into 15 plots with regular shapes and dimensions ($25 \times 50$ $m^2$).

The measurement of smoke emissions was performed in order to evaluate the contribution of different fire stages and burning conditions to the total volatile organic compounds (VOC) emissions. The applied technique for the measurement of VOC emissions consisted on sampling the smoke into Tedlar bags using an appropriate pumping device, as shown in Fig. 12.3. Samples were then kept in a cool

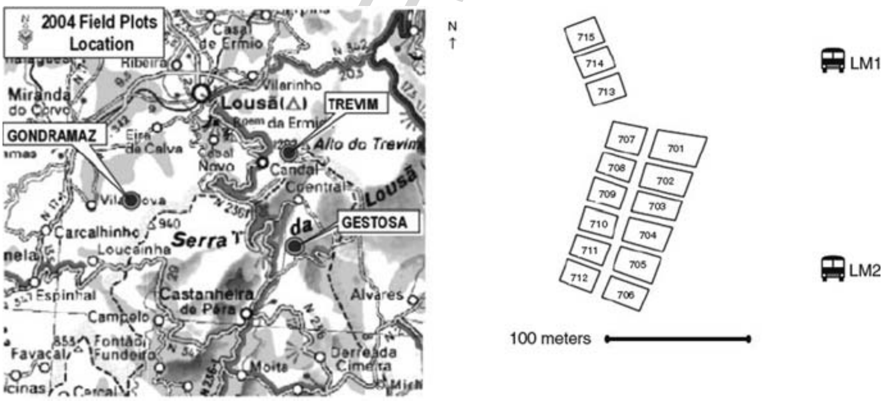


**Fig. 12.1** Map and schematic view of 2004 plots and location of mobile laboratories, in Trevim area

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**Fig. 12.2** Images from 2004 field fire experiments

**Fig. 12.3** Smoke sampling technique during smouldering phase (left) and example of a filled Tedlar bag (right)

and dark environment. Subsequent laboratorial analyses consisted in submitting the samples to a gas chromatography technique with a flame ionisation detector (FID).

This technique allowed the sampling of smoke during the different fire stages (flaming and smouldering) and for vegetation treated or untreated with retardant, enabling to determine specific emissions for different burning conditions. Figure 12.4 shows two examples of the sampling procedure with and without retardant.

In figure 12.5 the concentration of VOC for each plot, with and without retardant, is plotted. The burns of plots 712, 713 and 714 present a considerable increase on the amount of VOC emitted during the combustion of vegetation treated with retardant.

Almost all the samples registered very high values of emitted VOC. For untreated vegetation the VOC maximum measured value reached 1,930 mg $Nm^{-3}$. The reason why the measurements were so high, particularly when compared to previous experiments (Miranda and Borrego 2002), is the fact that the sampling location was much closer to the burning vegetation causing the sampled smoke to have lower dilution.

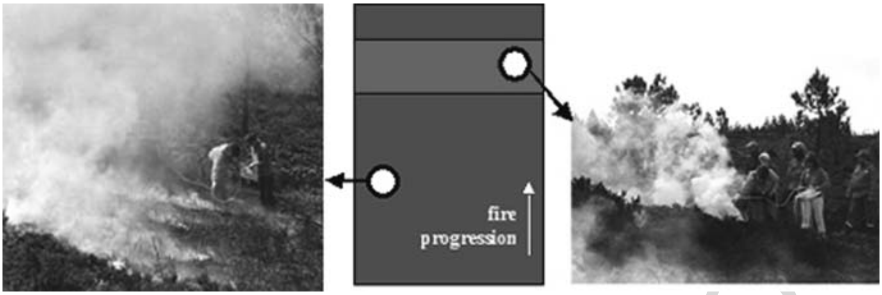


**Fig. 12.4** Central image represents a typical layout of the plots. Left image shows the smoke sampling with untreated vegetation and right image with treated one

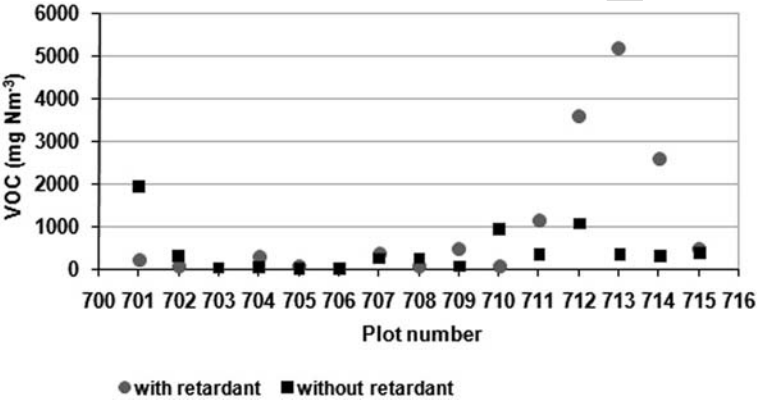


**Fig. 12.5** Representation of the concentration of VOC emitted for each plot with and without the presence of retardant

Due to the small size of the plots and the low fuel load, the fire intensity of the field experiments in 2004 was not as high as in previous years, allowing a sampling much closer to the combustion.

## 12.3 Forest Fires and Air Quality

The current knowledge about the contribution of forest fires to the total atmospheric emissions indicates a close relationship between forest fires and air quality. However, it is not always easy to identify air pollution episodes caused or exacerbated by forest fires. Gases and particles emitted from forest fires are transported and dispersed in the atmosphere and their effects on air quality can occur far from the emitting source. Although major wildfires are limited to some hundreds of hectares, their impacts, with no natural or political boundaries, can be felt and reported far beyond the physical limits of the fire spread. Depending on meteorological condi-

tions, smoke plumes and haze layers can persist in the atmosphere for long periods of time and prevailing conditions will influence the chemical and optical characteristics of the plume.

Despite the current scientific evidences on the subject, the link between forest fires and air quality is not commonly made. From the point of view of the community dealing with the fire the main concern regards its direct effects, such as human fatalities and property damage. On the other side, from the air quality community's perspective air pollution problems are usually analyzed only considering the main anthropogenic sources, particularly the classic industrial and road transport sectors.

The needed evaluation of the effects of forest fires on the air quality can be based on measurements or/and on modelling estimates.

### *12.3.1 Air Quality Measurements*

During the experimental 2004 fires, two mobile laboratories (LM) were parked near the burning plots (see Fig. 12.6) and continuously measured $PM_{2.5}$, $PM_{10}$, $NO_2$, nitrogen monoxide (NO), and CO levels. Figure 12.6 shows one of the mobile laboratories.

Distinct techniques and equipment were used to obtain the concentrations of the different pollutants. The description of these techniques and equipment can be found in Valente et al. (2007). Aiming to better understand the effects of these experimental fires on the air quality, the measured results were compared to the European air quality legislation values, which are also the Portuguese standards (see Table 12.3).

Figure 12.7 depicts the measured concentrations at LM1 of NO and $NO_2$ (5 min average), and $PM_{10}$ (15 min average), for the second day of the experiments, when


**Fig. 12.6** Mobile laboratory used during 2004 experiments for air quality and meteorological data acquisition. Outside (*left*) and inside (*right*) views

**Table 12.3** – Air quality limit values for the protection of human health established by European legislation

| Pollutant | Limit value | Averaging period | Directive of the Council |
|---|---|---|---|
| $PM_{10}$ | 50 μg $m^{-3}$ | 24 h | 1999/30/EC |
| $NO_2$ | 200 μg $m^{-3}$ | 1 h | 1999/30/EC |
| $SO_2$ | 350 μg $m^{-3}$ | 1 h | 1999/30/EC |
| CO | 10 mg $m^{-3}$ | Maximum daily 8-hour mean | 2000/69/EC |

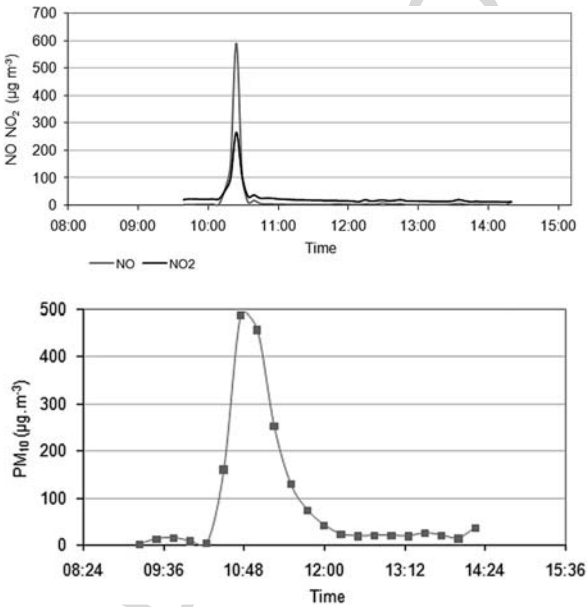


**Fig. 12.7** Measured concentration values (μg $m^{-3}$) of NO and $NO_2$, and $PM_{10}$ in LM1 on 12 May 2004

plots 702, 701 and 707 were burnt according to the following ignition times: 09:50; 10:10; and 10:50, respectively.

A very high peak value of 275 μg $m^{-3}$ was registered for $NO_2$ concentrations. Nevertheless, the hourly averages never exceeded the hourly European limit for $NO_2$. In what regards NO, when the plume reached the mobile laboratory, due to the proximity with the emission location and its position downwind of the plume, the values were quite high, reaching 600 μg $m^{-3}$.

The calculated daily mean of $PM_{10}$ concentration, 33 μg $m^{-3}$, did not surpass the limit value established by the European legislation and only during approximately three hours this 50 μg $m^{-3}$ limit value was exceeded. However, this direct comparison of measurements and European air quality thresholds has to be carefully analysed, because only the monitoring effect of a small burning plot during a small period of time was taken, while standards are established for longer averaging periods.

Although the burns took place only over a short period of time, the registered concentration values indicate that levels of some concern are attained even in small sized fires.

## *12.3.2 Air Quality Modelling*

The application of numerical air quality modelling systems is very useful for evaluating and assessing air quality levels in areas affected by forest fires. Several specific/dedicated models have been developed in the past for the simulation of smoke transport and dispersion (Breyfogle and Ferguson 1996; Miranda 1999). More recently under a collaborative and coordinated USA effort to model smoke impacts, the BlueSky Smoke Modelling Consortium was established in order to develop and apply a real-time smoke modelling to support fire operations and smoke management (Ferguson et al. 2001; Sestak et al. 2002). At the European level some modelling works were also already developed and applied, e.g. Miranda (2004), Hodzic et al. (2007) and Miranda et al. (2007). The main purpose of the two following case studies is to present two modelling exercises related to the impact of summer 2003 Portuguese forest fires on air quality.

### **12.3.2.1 Case-Study 1 – August 2003**

Portugal faced in 2003 the worst fire season ever recorded. There were 4,645 fires (with an area burned per fire above 1 ha) burning 8.6% of the total Portuguese forest area (EC 2004).

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A great number of fires occurred in August, with 86% (357,790 ha) of the total annual burned area. The air quality modelling application was performed using the LOTOS-EUROS system (Schaap et al. 2008), an operational 3D chemistry transport model aimed to simulate air pollution in the lower troposphere. The system was applied first at a continental scale (with $0.5° \times 0.25°$, approximately $35 \times 25$ km) and then to mainland Portugal domain, using the same physics and a simple one-way nesting technique, with $17.5 \times 12.5$ km horizontal resolution.

Simulations were done for August 2003, regarding gaseous and particulate compounds. A baseline simulation (BS), including "conventional" emissions, and a forest fire simulation (FS), which also considered emissions from forest fires larger than 100 ha were carried out. Hence, forest fire emission values, which were estimated using the methodology previously described, were added to the anthropogenic and biogenic grid emissions, according to the fire location and assuming a uniform fire spread and a constant injection altitude in the dynamic mixing layer. More details about this particular case study can be found in Miranda et al. (2007).

Modelling results were compared to background monitoring data from the regional air quality networks. Some statistical parameters were used to evaluate the simulations results: root mean square error (RMSE), systematic error (BIAS) and correlation coefficient (r). Table 12.4 present the statistical analysis for both simulations (with and without forest fire emissions), for $PM_{10}$ and O3. Results are analysed considering the averages for each Portuguese district.

**Table 12.4** Statistical analysis of models performance for BS and FS, for $PM_{10}$ and $O_3$

| | **$PM_{10}$** | | | | | | **$O_3$** | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | RMSE (μg m$^{-3}$) | | BIAS (μg m$^{-3}$) | | r | | RMSE (μg m$^{-3}$) | | BIAS (μg m$^{-3}$) | | r | |
| **District** | BS | FS | BS | BS | FS | BS | BS | FS | BS | BS | FS | BS |
| Aveiro | 16.43 | 15.23 | 41.28 | 34.57 | 0.45 | 0.47 | 30.56 | 30.85 | –15.24 | –20.21 | 0.71 | 0.72 |
| Castelo Branco | – | – | – | – | – | – | 31.50 | 30.85 | 10.00 | 5.94 | 0.49 | 0.53 |
| Coimbra | 18.72 | 15.77 | 53.11 | 37.75 | 0.48 | 0.73 | 29.49 | 28.64 | –9.77 | –14.48 | 0.72 | 0.76 |
| Leiria | 16.95 | 14.48 | 41.17 | 29.30 | 0.48 | 0.67 | – | – | – | – | – | – |
| Lisboa | 13.27 | 12.74 | 24.94 | 19.99 | 0.39 | 0.65 | 31.34 | 31.29 | 7.55 | 4.96 | 0.51 | 0.54 |
| Porto | 17.01 | 16.37 | 43.85 | 40.74 | 0.51 | 0.67 | 28.44 | 29.00 | –13.94 | –16.48 | 0.67 | 0.66 |
| Santarém | 17.28 | 16.64 | 24.56 | 23.06 | 0.27 | 0.51 | 36.64 | 37.16 | 23.14 | 21.67 | 0.46 | 0.43 |
| Setúbal | 14.87 | 13.89 | 33.78 | 27.07 | 0.37 | 0.68 | 29.25 | 29.28 | –2.60 | –5.52 | 0.60 | 0.62 |
| **Average** | **16.36** | **15.02** | **37.53** | **30.35** | **0.42** | **0.63** | **31.03** | **31.01** | **–0.12** | **–3.45** | **0.59** | **0.61** |

$$RMSE = \sqrt{\sum_{i=1}^{N} (O_i - M_i)^2} \qquad \mathrm{BIAS} = \frac{1}{\mathrm{N}} \sum_{i}^{N} (O_i - M_i) \qquad \mathrm{r} = \frac{\sum_{i=1}^{N} (O_i - \overline{O}) - (M_i - \overline{M})}{\sqrt{\sum_{i=1}^{N} (O_i - \overline{O})^2 \sum_{i=1}^{N} (M_i - \overline{M})^2}}$$

N is the number of samples, $O_i$ are observations and $M_i$ are model predictions

The model performance improved considerably when forest fire emissions were included. In average, RMSE decreases 8% for $PM_{10}$, and the correlation coefficient increases from 0.42 to 0.63. LOTOS-EUROS present a tendency to underestimate the $PM_{10}$ values in both simulations.

Regarding $O_3$ results improvements were also obtained when forest fire emissions were included. However the effect was not as important as for $PM_{10}$. Estimated biases do not present a clear trend, but in average it is possible to indentify a tendency to overestimate $O_3$.

In order to contribute to the analysis of the spatial impact of forest fire emissions on the air quality, Fig. 12.8 shows the spatial differences of the $PM_{10}$ daily values between both simulations (FS–BS), for one of the most critical days (August, 3). For this specific day, the impact of forest fires is higher at the central inland part of Portugal, and the $PM_{10}$ daily mean difference can reach 200 $\mu g\ m^{-3}$.

#### 12.3.2.2 Case-Study 2–13th September 2003

Lisbon suffered the effects of smoke from forest fires north of its urban area in September 2003, particularly in the 13th of September, when several air quality stations registered extremely high concentrations due to fire emissions and their transport from surrounding areas. The Lisbon airshed, with a population of 3.5 million inhabitants, is the most important urban centre in Portugal. It was built in a very complex topographic region, dominated by a large estuary and multiple hills and surrounded by small mountain ranges with elevations over 400 m above sea level.

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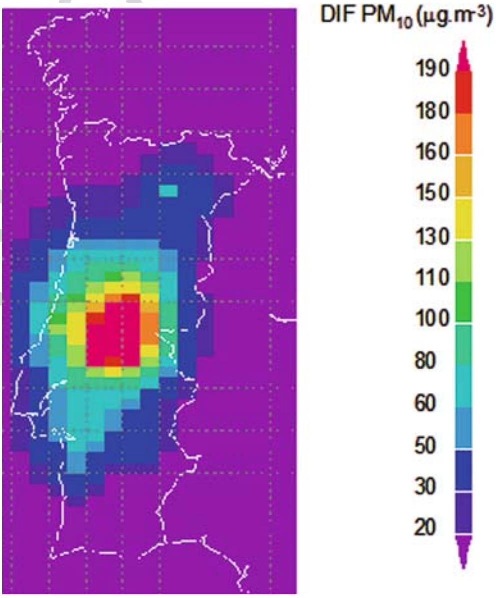


**Fig. 12.8** Spatial differences of $PM_{10}$ daily means ($\mu g$ m–3) between simulation with (FS) and without (BS) forest fire emissions, for the 3rd of August*

*For colour version of this figure, please refer Colour Plate Section.

Because of its urban/wildland characteristics, high population density, and hence higher risk of human exposure to smoke, and the high levels of pollutants registered, Lisbon forest fires were a very interesting case for the study of the influence of forest fires emissions on air quality.

The numerical modelling system AIRFIRE (Miranda 2004) was developed to take into account the possible impact of forest fires on photochemical production. Using data available for the 13th of September 2003, AIRFIRE was applied to a modelling domain of $200 \times 200$ km$^2$ with a horizontal resolution of $4 \times 4$ km$^2$. This domain was chosen in order to consider mesoscale circulations, such as sea breezes in the Lisbon area. More details about this particular case study can be found in Miranda et al. (2005c).

Figure 12.9 shows surface $PM_{10}$ hourly concentration values for two distinct situations: (i) considering Lisbon emissions for a normal week day; and (ii) considering Lisbon emissions and emissions from the forest fires. The influence from the fires on $PM_{10}$ concentrations is clearly visible with larger pollutant clouds and higher concentrations.

The urban area of Lisbon has an air quality monitoring network that includes several stations with different typologies (urban background or urban traffic), according to location and environmental criteria. Data from those monitoring stations allowed the evaluation of the model performance when simulating the Lisbon air quality affected by smoke from forest fires. Figure 12.10 presents the comparison between simulated and observed $PM_{10}$ hourly concentrations, for some of Lisbon's air quality stations, for the 13th of September 2003.

A reasonable agreement between simulated and measured values was found. However, in Av. da Liberdade monitoring location simulated values were bellow measured ones, mainly at the end of the day.

Table 12.5 presents the statistical analysis of the simulation performance for those monitoring stations regarding $PM_{10}$ and $O_3$ concentration values. For $O_3$, the positive bias presented in the two stations indicates that simulated concentrations are under-estimated; the correlation coefficient is above 0.69 showing a good skill of the model in terms of natural variability of the data; the obtained deviations (RMSE) are also acceptable presenting similar magnitudes for both stations. For $PM_{10}$ the obtained statistics are quite satisfactory, with Entrecampos station presenting the best results. The positive bias in Av. da Liberdade and Loures points to an under-estimation of concentrations. Av. da Liberdade has a higher RMSE due to the peak values that were registered and not estimated at the end of the afternoon. Since Av. da Liberdade is a traffic station, strongly influenced by local emissions, this is probably not well represented in the emissions grid resolution.

## 12.4 Conclusions

The effect of forest fires on air quality is an issue of concern in many regions of the world, including the southern European countries. Emissions from forest fires may cause substantial exceedances of the air quality thresholds and there is a strong need

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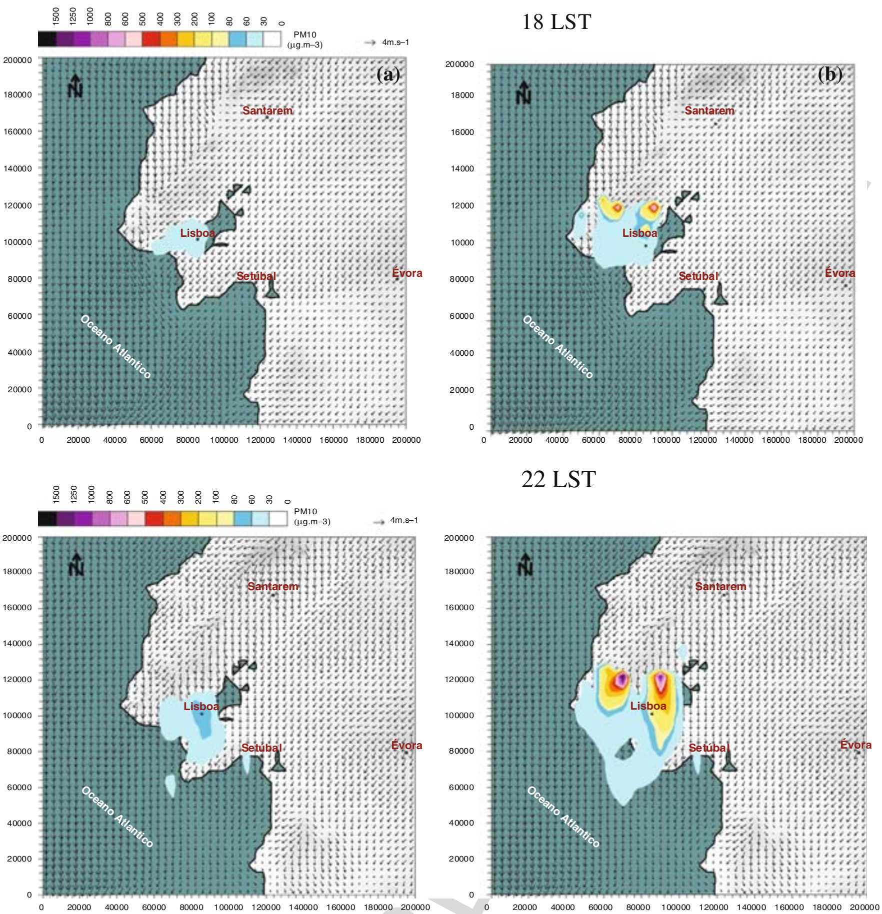


**Fig. 12.9** Wind and $PM_{10}$ ($\mu g\ m^{-3}$) concentration fields at 18:00 and 22:00 Local Standard Time considering: (i) only Lisbon emissions, and; (ii) Lisbon and fire emissions*

to take into account the role of forest fires when defining management strategies for air quality. This chapter illustrates how forest fires and air quality issues can be linked through two main approaches: measuring and modelling.

Experimental field fires represent a valuable tool for understanding wildfires in all its extension: behaviour, impacts on environment, security conditions and health, suppression techniques efficiency, among others. The participation in the Lousã fire experiments, particularly in the year 2004, has been a profitable opportunity to collect air pollutants concentrations data. Distinct techniques and equipment were used to obtain the concentrations of the different pollutants. However, and this is one of the problems inherent to field experiments, the exact conditions of each burn are not reproducible, in particular the meteorological conditions, the terrain characteristics,

*For colour version of this figure, please refer Colour Plate Section.

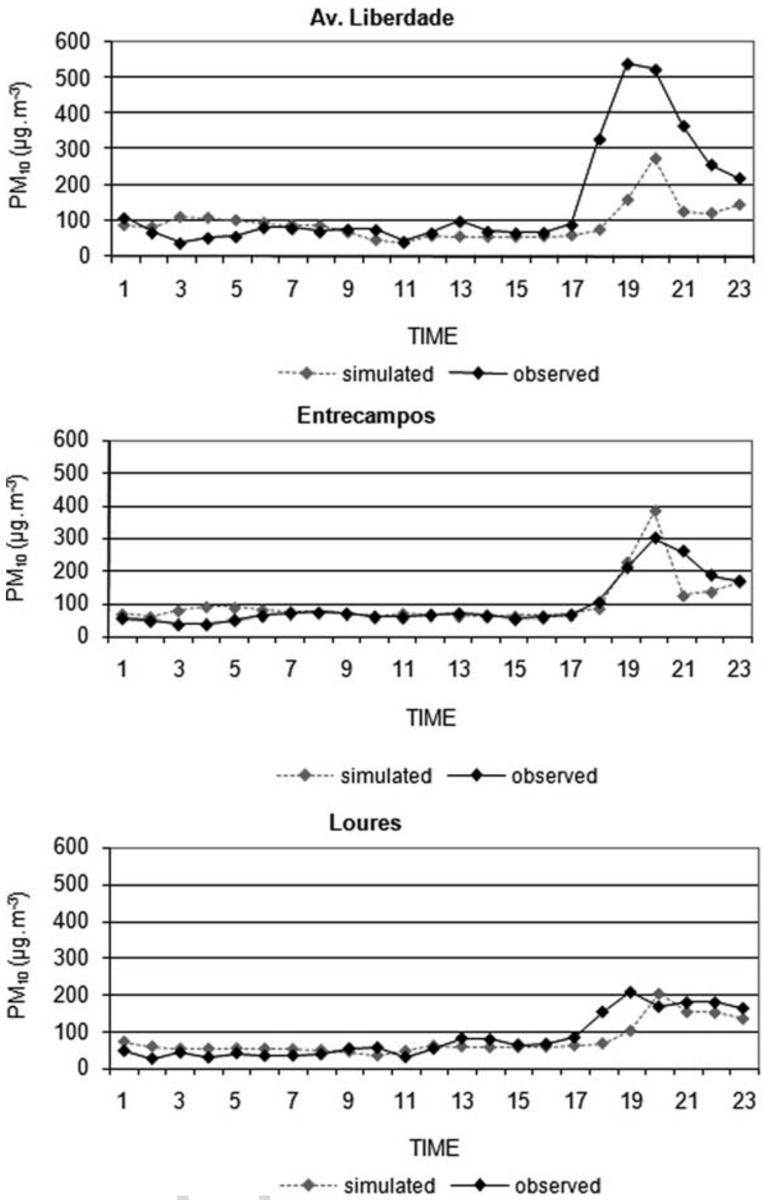


**Fig. 12.10** Temporal evolution of simulated and measured $PM_{10}$ hourly concentration (mg m–3) values in Av. da Liberdade, Entrecampos and Loures air quality monitoring stations

the type and load of fuel. Even with this limitation it was possible to conclude that despite the small size of the burning plots when compared to wildfires, the measured levels of pollutants were not negligible.

**Table 12.5** Statistical analysis of models performance for $PM_{10}$ and $O_3$ concentration values

| | $PM_{10}$ | | | $O_3$ | | |
|---|---|---|---|---|---|---|
| **Monitoring station** | **RMSE ($\mu$g m$^{-3}$)** | **BIAS ($\mu$g m$^{-3}$)** | **r** | **RMSE ($\mu$g m$^{-3}$)** | **BIAS ($\mu$g m$^{-3}$)** | **r** |
| Av. Liberdade | 126.9 | 56.6 | 0.77 | – | – | – |
| Entrecampos | 35.3 | –4.7 | 0.88 | 35.9 | 32.8 | 0.94 |
| Loures | 34.6 | 8.5 | 0.81 | 55.8 | 39.2 | 0.69 |

The application of numerical air quality modelling systems is also an added value when evaluating and assessing air quality levels in areas affected by forest fires. Two case-studies were reported, which were based on two approaches: a top-down and a bottom up. The top-down that was applied to Portugal and the case study of August of 2003 implied the simulation of a larger number of fires and the use of a coarser grid resolution. On the other hand, the one day Lisbon case study allowed a higher spatial resolution and the treatment and characterisation of forest fires with much more detail. Both modelling approaches are useful. The bottom up can be applied to simulate a specific air pollution episode related to the occurrence of forest fires. In this case the information from the numerical system, which can be applied almost in real time, can help to identify critical areas where persons are exposed to high levels of air pollutants. The top down approach is quite useful for the characterization and the evaluation of the air quality by each European member state or at a higher level by the European Commission.

Finally, and as a last recommendation, environmental policies, in particular the south-European ones must integrate both, the traditional air pollution-oriented and the forested-land management issues into a unique system. Better forested-land management can help to reduce both the number of air pollution episodes and the risk of unwanted fires.

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# Chapter 12

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# Chapter 13
# Forest Fires in the European Mediterranean Region: Mapping and Analysis of Burned Areas

**Jesús San-Miguel-Ayanz, Jose M.C. Pereira, Roberto Boca, Peter Strobl, Jan Kucera and Anssi Pekkarinen**

**Abstract** Approximately 60,000 fires occur in the European Mediterranean region every year. On average, they burn approximately half a million ha of forest areas. The mapping of areas burned by forest fires is of critical importance for the analysis of fire impact and for the monitoring of fire recurrence and vegetation recovery in affected areas. An important contribution of remote sensing in wildfire monitoring is the mapping and analysis of burnt areas. Areas affected by forest fires present a distinct spectral response in the optical and infrared part of the electromagnetic spectrum, which allows the mapping of these surfaces with the use of passive satellite remote sensors. On the side of active sensors, the synthetic aperture radar is also used for this purpose, especially in boreal regions, where continuous cloud cover prevents the use of optical sensors. Although remote sensing of burnt areas in the Mediterranean region has a long history, the operational implementation of remote sensing methods in national or regional Administrations is fairly new. The need of specialized personnel, dedicated hardware and software for image processing, and the lack of automation of the classification methods has prevented its operational implementation until recently. A large contribution to the success in the current use of remote sensing for burned area mapping is due to the increased processing capacity of modern computers and the ever increasing availability of remotely sensed imagery from a large variety of sensors, from the low spatial resolution in the order of km to the very high spatial detailed imagery in the order of cm. The choice of imagery depends, obviously, on the application at regional or local scale, and the frequency for which updates of fire perimeters are needed. The current chapter reviews the application of remote sensing for burned area mapping and its use in the Mediterranean region for operational fire monitoring. Additionally, it provides insights on future opportunities for the improvement of existing mechanisms, the acquisition and processing of satellite imagery, and the analysis of burnt areas.

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## 13.1 Forest Fires in the European Mediterranean Region

Forest fires are an integral component of the European Mediterranean landscape. The have existed probably before the human presence and they have co-existed with all the human civilizations that lived in the region. Although historical records of fires in the region exist since remote times, fire statistics are only available since the late 1970s. In fact, fairly reliable data for the largest European Mediterranean countries exist in the European Forest Fire Information System since the 1980s. On average, about 60,000 fires occur every year, burning approximately half a million ha of forest areas. The trend on the number of fires in the region, which is presented in Fig. 13.1, shows a clear increase in the number of fires from the 1980s until today. However, a noticeable step is shown in the 1990s. The reason for this may be found in the improvement of the methods for the collection of data in the countries, and also in the implementation of the European Regulation EC 2158/92 that aimed at the establishment of forest fire information systems in the European countries. In the last decade, in which the data are certainly reliable, there is not a clear trend in the number of forest fires in the EU Mediterranean region (see Fig. 13.1). Regarding the total burnt area in the European Mediterranean region, no historical maps of those burnt areas are available. However, national statistics based on the estimate of burnt areas are available for the European Union Mediterranean countries. The trends of forest areas burned by forest fires do not show a clear trend in the last decades. Moreover, even though figures in terms of total burnt area may be similar between some years, the spatial distribution of the fires differed largely from year to year, especially during the last decade. Accurate mapping of the heaviest damage caused by forest fires are available at EFFIS since the year 2000. Those include fires larger than 40 ha, which represent approximately 80% of the total forest area burned in the Mediterranean region. The methods used in EFFIS, as well as other remote sensing approaches for burnt area mapping are presented in the sections ahead.

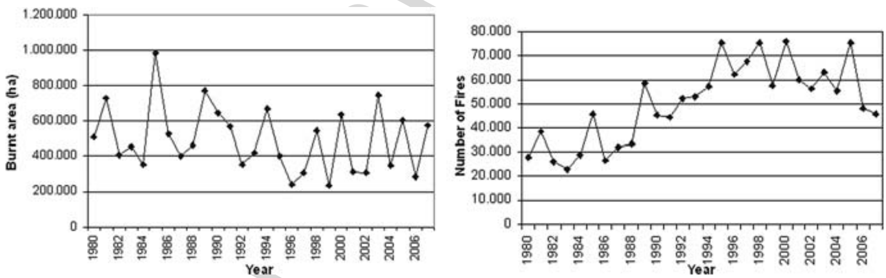


**Fig. 13.1** Burnt areas and number of fires in the European Mediterranean region
Source: Includes data from the Portugal, Spain, France, Italy, and Greece

## 13.2 Review of the Use of Remote Sensing for Wildfire Monitoring

Remote sensing techniques are used in all the phases of wildland fire monitoring. Pre-fire applications include those of fuel mapping and analysis of fire danger conditions, in relation to the status of the vegetation and water content of the fuels. Active fire detection from remote sensing is based on the detection of thermal anomalies produced by the high temperature of burning fuels in the mid-infrared and thermal part of the electromagnetic spectrum. Post-fire applications include the mapping of the extent of burnt areas, the analysis of fire severity, and finally the evaluation of the recovery of vegetation in the fire affected areas.

Fuel mapping from optical remotely sensed data has been carried out at different scales and spatial resolutions. Most of the studies performed the mapping of fuels using high spatial resolution imagery from the Landsat MSS (Multispectral Scanner) or TM (Thematic Mapper) and the SPOT-HRV (Systeme Pour l'Observation de la Terre – Haute Resolution Visible) sensors; some studies used the ASTER sensor for the same purposes (Lasaponara and Lanorte 2007). Higher spatial resolution imagery was used for local studies by Giakoumakis et al. (2002), Arroyo AQ1 et al. (2005), Gitas et al. (2006). In the area of active sensors, LIDAR systems have proven very useful for the mapping of fuel properties at local scales. Fuel properties were also extracted from different Synthetic Aperture Radar sensors, although the actual mapping of fuels was never achieved (Ranson and Sun 1997; Hyyppa et al. 2000; San-Miguel-Ayanz 1996). Arroyo et al. (2008) presented a comprehensive review of methods and sensors for fuel mapping from remote sensing.

Remote sensing has also been used for assessing fuel condition in the computation of forest fire danger. Authors computed several indices either related to the photosynthetic activity of the vegetation as the NDVI or its relative inter-annual and intra-annual variation (Chuvieco et al. 1999; Gabban et al. 2006), or related to AQ2 the water content in the vegetation (Chuvieco et al. 2002; Hao and Qu 2007). Some authors combined this information with additional information on fuels or meteorology to assess fire danger (Burgan et al. 1998; Ceccato et al. 2001; Sebastián-López et al. 2002). A review on the use of near infrared information for analyzing water content in vegetation is presented in Clevers et al. (2008).

Several remote sensors have been used for detecting and mapping active fires at regional to global scales. At global scales GOES (Schroeder et al. 2008) and AVHRR (Pozo et al. 1997; Boles and Verbyla 2000) were used for the analysis of burnt areas and emission at continental scales. Higher spatial resolution and fire detection capabilities in the MODIS sensor allowed obtaining improved active fire detection at regional and local scales (Giglio et al. 2003). However, the accuracy and reliability of the products obtained from these sensors had a great deal of variation and has not been, in most cases, systematically assessed (Mota et al. 2006). Its applicability focuses mainly on global assessment of fire activity and it is not intended for active fire detection for fire fighting or the compilation of reliable fire statistics. A review on the applicability of remote sensing for operational active fire detection is presented in San-Miguel-Ayanz et al. (2005).

One of the most widely used applications of remote sensing is the mapping and analysis of burnt areas. Burned areas exhibit a typical spectral response, which distinguishes them from healthy vegetation. A review of these characteristics was presented by Pereira et al. (1999). A variety of sensors has been used for this purpose, from the global scales (GOES; AVHRR, ATSR), through the regional scales (WiFS, MODIS, DMC) up to national (TM; SPOT-HRV, ASTER) and local scales (IKONOS, QUICKBIRD, FORMOSAT). The next sections of this chapter review in detail the methods (I think its not only methods, but also results and applications, wouldn't you say?) used to characterize and map burnt areas in the Mediterranean region.

Once fires have taken place it is important assessing the degree of the damage, and monitoring the recovery of the vegetation. The analysis of the degree to which vegetation is affected by fires is referred to as fire severity. Since fire severity is related to decrease photosynthetic activity or even suppression of vegetation, soil exposure and physical changes in the ground, it can be related to changes in the spectral response before and after the fires. Many different remote sensing methods were used to assess fire severity (Boer et al. 2008; De Santis et al. 2007; Díaz-Delgado et al. 2003; Key and Benson 2005). Some of these indices were also used to assess the vegetation recovery and the post-fire vegetation dynamics (Röder et al. 2008). A detailed review of this topic is presented in another chapter of this book.

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## 13.3 Burnt Area Mapping in the European Mediterranean Region

### *13.3.1 Mapping Burned Areas: From Regional to Local Scales*

The use of remote sensing for mapping burnt areas has a long history in the European Mediterranean region. Pereira et al. (1999) described in detail the spectral characterization of burnt areas and the discrimination for their classification from satellite imagery.

At the regional scale, mapping of burnt areas was performed with AVHRR data already in the 1980s, although it focused mainly on large fire events. Examples of regional burnt area mapping in the European Mediterranean region were presented by Pereira et al. (1999). The accuracy of the results was fund to be about 80% for large fires, and the methods were considered suitable only for fires larger than 1,000 ha, and reliable for fires larger than 2,000 ha. However, the mapping of those fires would correspond only to approximately 30% and 21%, respectively, of the total burnt area in the European Mediterranean region. In the late 1990s, sensors of medium spatial resolution such as the Russian RESOURS-04 and the Indian IRS WiFS provided new possibilities for the mapping of fires of smaller size (San-Miguel-Ayanz et al. 1999; Pereira 1999b). Nevertheless, these sensors did not provide the required revisit frequency or area coverage for the mapping of burnt areas at regional level. Moreover, the data did not have enough radiometric quality and

spectral information for the proper discrimination of burnt areas. With the launch of the MODIS sensor on board of the TERRA and ACQUA satellites, a new capability for regional mapping of burnt areas was put in place. Better radiometry and higher spectral information of the MODIS sensor provided the right data for the discrimination of burnt areas at regional and global scales. The simultaneity in the operation of both satellites provided higher frequency in data acquisition and enough revisit time for accurate mapping of burnt areas. The availability of free data of medium spatial resolution from the MODIS sensors since 2000 provided a definite impulse for the use of remote sensing at the regional and global scales (Justice et al. 2002). MODIS data are used in the European Forest Fire Information System for mapping the burnt areas of approximately 40 ha or larger since the year 2003. Since then, updated maps of burnt areas for southern Europe are provided routinely in the system. The MERIS sensor, on board of the ENVISAT satellite, provided high quality radiometry and adequate spectral information. However, the lower revisit time and the lack of adequate mechanisms for data distribution by the European Space Agency (ESA) prevented the wider use of these data for scientific and operation mapping of fire effects.

The accurate mapping of burnt areas requires the use of high spatial resolution imagery. Burned area mapping was initially based on the use of high resolution imagery provided mainly by the Landsat Thematic Mapper sensor (Michalek et al. 2000; Pereira and Setzer 1993; Chuvieco and Congalton 1998), complemented in some cases by the SPOT and ASTER sensors. Some analyses were also performed with the use of the LISS-3 sensor of the IRS Indian satellite, and the RESURS MSU-K (San-Miguel-Ayanz et al. 1998). A variety of indices were computed from the original spectral bands and used to improve the mapping of burnt areas (Pereira et al. 1997; Li et al. 2000; Chuvieco et al. 2002). However, this exercise was, in most cases, limited to the mapping of burnt areas at local and sub-national scale. The exception to this is the case of Portugal. where an operational system capable of processing Landsat TM scenes for mapping of burnt areas was put in place. This system was complemented since 2003 with a processing chain for MODIS data, which provides accurate estimates of the burnt areas throughout the year. A detailed description of this system is provided in the next section.

The availability of multiple sensors acquiring satellite imagery of high spatial resolution (or very high spatial resolution) permits the combined used of multiple sensors for the accurate mapping of burnt areas. Several pilot projects demonstrating the theoretical capacity on the use of multiple sensors for mapping of burnt areas at local and sub-national scales were launched in the context of the Global Monitoring for Environment and Security Service Elements (GSE) ESA program (e.g. RISK-EOS). However, the cost of the acquisition of the data and complexity of the pre-processing and analysis of the images prevented its implementation. Demonstration was therefore reduced to regions within several countries. Nevertheless, this set-up of simultaneous acquisition of satellite imagery from several sensors permitted the precise mapping of burnt areas in critical fire events, such as the fires in north-western Spain in 2006 and those in Greece in 2007. In the case of major fire events, the required satellite remote sensing data are acquired by a series of satel-

lite agencies through the so-called International Space Charter, which was declared formally operational on November 1, 2000. The International Charter aims at providing a unified system of space data acquisition and delivery to those affected by natural or man-made disasters through “authorized users”, which are generally the civil protection organizations in the countries. Requests to the International Space Charter allow the provision of the available data from a series of satellites, including RADARSAT, ERS, ENVISAT, SPOT, IRS, SAC-C, NOAA satellites, LANDSAT, ALOS, DMC in order to obtain data and information on a disaster occurrence.

## *13.3.2 Methods for Burned Area Mapping*

The methods used for the classification of the satellite imagery and the mapping of burnt areas vary with the radiometric characteristics of the remotely sensed data used for this purpose and the spatial and temporal resolution of the data (Pereira et al. 1997). The techniques vary depending on the available data, and can be grouped into single image analysis, in which one image acquired after the fire events is available, change detection techniques in which pre-fire and post-fire conditions are combined to discriminate changes, and finally time series analysis in which a fairly complete set of pre-fire and post-fire scenes are used.

The methods for mapping burned areas from remote sensing are many. These include supervised, unsupervised, and mixed methods, in which the supervised and unsupervised approaches are combined. Mapping of burnt areas consist on the spectral discrimination of the burnt surface with respect to the other land cover classes in the images. Land cover areas that may raise confusion and lead to commission errors classifying as burnt areas that are not, include water bodies, shallow water areas, shadows, and to a lesser extent urban areas in which a variety of land types are mixed. Omission errors may occur in areas that are partially burnt or those in which the above forest canopy is not fully burnt as in the case of ground surface fires. For the purpose of the current analysis, the methods have been grouped in two classes, those based on the analysis of imagery acquired at one point in time (Single image analysis), and those that use multi-temporal imagery (Multi-temporal image analysis). Some studies analyzed the performance of each of these methods for mapping burnt areas (San-Miguel-Ayanz et al. 1999), although there is not an overall agreement of which methodology achieves best results.

### 13.3.2.1 Single Image Analysis

Single image analysis is commonly use for the processing of medium to high or very high satellite imagery, while the following methods of change detection and time series analysis are often used for coarser spatial resolution imager. Any of the techniques for classification of remotely sensed data can be used for mapping burnt areas.

It is not the purpose of this chapter to describe al the possible methods, but to illustrate which of those used for burnt area mapping in previous studies in the

Mediterranean regions. Most the studies used supervised classification, in which the classifier is trained to a reference set of burnt areas, in order to allow identifying the rest of the burnt scars on the image. A combined supervised and unsupervised classification applied by Chuvieco and Congalton (1998) and Castellana et al. (2007) achieved improved results when compared to each of the classification methods independently. Spectral mixing analysis was used on Landsat TM by Caetano et al. 1994 with positive results that eliminated some of the problems associated to topographic effects. Logistic regression as well as Intensity-Hue-Saturation (HIS) was applied by Koutsias and Karteris 1998 achieving high classification accuracy of local mapping of burnt areas in Greece. Often, classification is not applied on the original image bands, but on a series of so called vegetation indices, which are derived from the algebraic combination of the spectral bands. These indices are related to physical and physiological characteristics of the plants and help in discriminating healthy vegetation from stressed and scorched vegetation in the burnt areas. San-Miguel-Ayanz et al. (1999) proposed the use of the so-called Burnt Index (BI) for burnt area mapping on RESURS MSU-SK and IRS WiFS imagery. Chuvieco et al. (2002) presented a new index referred to as BAI (Burnt Area Index), which lead to improve mapping of burnt areas when compared with other widely used indices, including NDVI, GEMI, and SAVI. Additionally, Pereira (1999) carried out a comparative analysis of vegetation indices computed on single imagery for burnt area detection and mapping.

#### 13.3.2.2 Multi-Temporal Analysis

The mapping of burnt areas using change detection techniques involves the use of pre- and post-fire satellite imagery in a single classification stage. Additional information is gained on the conditions of the burnt area before the fire, which help in identifying those areas in which spectral response has changed and classify them as potential burnt areas. Although the methodology represents an improvement with respect to the single image classification, it presents additional complexity regarding the co-registration and radiometric normalization of the images. Potential errors may arise in relation to image illumination, clouds and cloud shadows detection and image compositing mechanisms (Vancutsem and Defourny 2009; Chen et al. 2005; Coppin et al. 2004).

The available methods for change detection include supervised and unsupervised approaches, or simple algebraic comparisons of the pre- and post-fire imagery such as image differencing. These methods can be applied on a per-pixel basis or in an object-based approach (Desclee et al. 2006; Bruzzone and Prieto 2000, 2002; Le Hegarat-Mascle et al. 2005). They can be used for the classification to remotely sensed data of any spatial resolution, although they were extensively used for the processing of coarse resolution imagery such as NOAA-AVHRR, SPOT VG, ATSR (Pereira 1999; Fernandez et al. 1997; Pu et al. 2007; Chuvieco et al. 2008a; Silva et al. 2005; Eva and Lambin 2008).

A suitable technique that has been often used for burnt area detection with multitemporal datasets is Principal Component Analysis. While the first principal compo-

nents tend to preserve the features that are unchanged, the subsequent components highlight areas in which changes took place, such as the burnt areas (Richards 1984; Milne 1986; Pereira 1992; Siljeström and Moreno-López 1995; Koutsias et al. 2009)

There are other change detection techniques as spectral mixture analysis (SMA) and regression analysis, although these have been rarely used for burnt area mapping. SMA aims at obtaining a complex signal from the features on the image as a linear combination of the individual spectral responses of pure components, referred to as end-members. Some examples of its applicability of this technique can be found in Caetano et al. (1994). Regression analysis was applied by Koutsias and Karteris (1998) for the classification of burned areas on Landsat TM imagery and by Silva et al. (2005) for correlating information of burned areas obtained from satellite imagery of different spatial resolution.

Although most of the change detection methods for burnt area mapping were applied to optical imagery, there are a series of examples in which data from active sensors such as the Synthetic Aperture Radar (SAR) were used. Although most of the studies were carried out in boreal forest (Kasischke et al. 1994; French et al. 1999; Siegert and Ruecker 2000; Menges et al. 2004), some examples for the Mediterranean area exist (Gimeno and San-Miguel-Ayanz 2004; Gimeno et al. 2005). Rather than the changes in vegetation condition and structure, the detection of burnt areas from SAR is based on the changes on moisture content in the burnt surface with respect to the unburned areas. Burnt areas tend to have higher moisture content than unburned areas, which reduces the backscatter. Thus, burnt areas appear as dark objects in relation to the surrounding non-affected areas.

## 13.4 European Research Projects

Remote sensing of burnt areas has been a relevant research topic of several European Union research projects in the last 10 years. As such, these research projects provided an impulse in the improvement of existing methods and the development of new ones in this field. Two of the most relevant projects were MEGAFIRES (1996–1998) and SPREAD Fire Spread Prevention and Mitigation (SPREAD-EVG1-CT-2001-00043).

MEGAFIRES (ENV-CT95-0256) was a project financed by the European Commission DG XII (currently DG Research) under the Environment and Climate Programme. Among other aspects, research on burnt area mapping using the AVHRR (Sousa et al. 2003) sensor was carried out. This work lead to the scientific publications that were cited in previous sections.

SPREAD project was carried out between 2002 and 2006. It included research in many aspects of fire monitoring, including remote sensing of forest fires and burnt area mapping. These later activities included research on the use of the WiFS, MODIS, QUICKBIRD and ASTER sensors.

After the SPREAD project, other EU funded projects aimed at the operationalization of the existing methodologies in the context of the Global Monitoring for

Environment and Security (GMES) joint initiative of the European Commission and the European Space Agency. Projects such as PREVIEW and RISK-EOS fall under this category. They aimed to the provision of services to local and regional partners in the countries and achieved a limited degree of success. Some other ESA projects aimed at creation of operational products at the national level. This was the case of the ITALSCAR project. The initial objective of the project was the production of maps for all fires larger than 1 ha in Italy on the basis of high resolution imagery, mainly from Landsat TM and SPOT HRV. However, a number of difficulties in the acquisition and process of the data did not permit achieving the expected results.

## 13.5 Towards Operational Mapping of Burnt Areas in the Mediterranean Region

As mentioned in previous sections, several projects aimed at the operational production of burnt area products. However, due to the limited funding, which did not cover the full cost of the operational chain, and the reduced duration, these projects they did not succeed in their attempt.

Nevertheless, operational remote sensing of burnt areas was achieved at the national and the European levels through other independent initiatives. At the national level, the long research experience of Pereira et al. permitted setting up a fully operational processing chain for the mapping of burnt areas from Landsat TM and ETM imagery. At the European level, the support of the DG ENV and JRC, and the consolidation of research results at the JRC, permitted the establishment of the processing chain in EFFIS on the basis of medium spatial resolution data (e.g. WiFS and MODIS).

The following sections review the implementation these operational burnt area mapping systems.

### *13.5.1 Country Experiences*

At the national level, Portugal is the only European country having an operational system for mapping burnt areas from satellite remote sensing imagery.

In Portugal. burned area mapping has been performed by the Department of Forestry, School of Agriculture (TU Lisbon) covering the entire portuguese mainland on an annual basis (1975 to the present), using Landsat imagery. Landsat MultiSpectral Scanner (MSS) data were used from 1975 to 1983 and Landsat Thematic Mapper (TM) /Enhanced Thematic Mapper (ETM+) imagery from 1984 to present. Mapping for the years 1984–1989 was done in collaboration with the Tropical Research Institute, Lisbon. During the MSS period the annual fire perimeter maps were developed with a minimum mapping unit of 35 ha, which was decreased to 5 ha for the TM/ETM+ period. Fire scars are mapped with a supervised classification approach based on the Classification and Regression

Trees (CART) algorithm (Breiman et al. 1984). This automatic classification phase is followed by very thorough visual inspection and on-screen editing of fire perimeters. Next, we perform a county-level comparison between the burned area estimates derived from satellite image classification, with ground data provided by the National Forest Authority and double-check areas where large discrepancies between the two estimates are found. During the 1980s, the Forest Service severely underestimated area burned. For example, in 1984 and 1985 Landsat-based burned area estimates were twice as large as those based on ground measurements. The quality of ground-based fire scar mapping has gradually improved, such that during the last decade discrepancies between the two sources of data were reduced to a few percent points of total area burned.

The Landsat-based annual fire perimeter maps are used for structural fire risk mapping (Pereira and Santos 2003) updated every year. These maps are referred in the national forest protection legislation and are used operationally by the National Forest Authority, the National Authority for Civil Protection and by large private landowners (mainly pulp and paper companies). Data from the fire perimeter atlas were used to support the development of the National Plan for Forest Protection Against Wildfires (APIF 2005). Silva et al. (2006) used some of the data to develop estimates of pyrogenic emissions for the 1990s, while Oliveira (2008) performed the longest and most detailed quantitative fire frequency analysis available in Europe, with 31 years (1975–2005) of data, corresponding to about 35000 fire perimeters. This is an ongoing project that DEF/ISA continues to develop under contract with the National Forest Authority. The map of burnt areas in Portugal, showing fire recurrence (number of times burned), is shown in Fig. 13.2.

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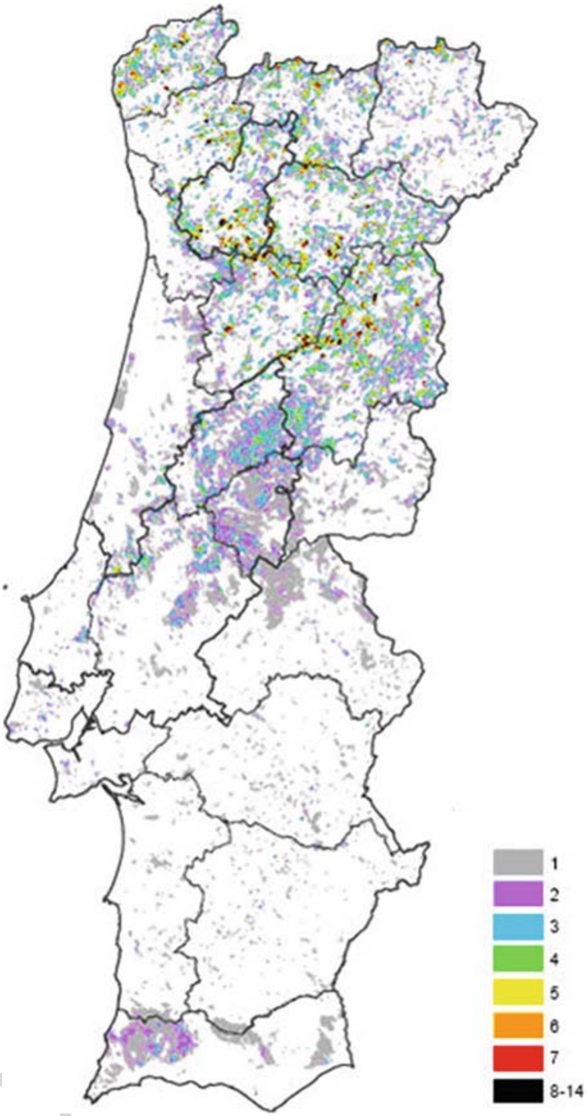
### *13.5.2 European Experiences/EFFIS*

The concept on the establishment of a European system to monitor forest fires started in 1998, when a first meeting for the discussion of this system took place with the participation of representatives of the European Union (EU) Member States, the European Directorate General Environment, and the Joint Research Centre was. After a research period of two years, dedicated to consolidate the main research findings in the area of forest fires, the European Forest Fire Information System (EFFIS) operated for the first time in the year 2000. It provided standardized European forest fire danger forecast for the EU Mediterranean region. Burnt area maps were produced at the sub-regional level during 1998 and 1999 on the basis of IRS WiFS and RESURS MSU-SK data. Only in the year 2000, EFFIS was capable of producing the first map of burnt areas at the European Mediterranean level on the basis of the WiFS data. Classification was performed on the basis of a single imagery acquired after the summer fire season, through the thresholding of derived vegetation indices (San-Miguel-Ayanz et al. 1998), and post-classification by visual interpretation. The ability for the production of accurate maps for those fires larger than 50 ha was tested in Portugal (Pereira 1999b). Testing on the use of MODIS data was performed from the year 2000 to the year 2002 and the first map of burnt areas

**Fig. 13.2** Number of times burned, 1975–2005 (from Oliveira 2008)*

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using this imagery was obtained in 2003. Since then, the processing chain has been further automated.

Currently, the processing chain includes a data pre-processing sub-system, which is operated by the German Aerospace Agency (DLR) (Fig. 13.3). Images are acquired during the whole year, although the core of the real-time processing is carried out from May to the end October every year. The scheme of satellite

*For colour version of this figure, please refer Colour Plate Section.

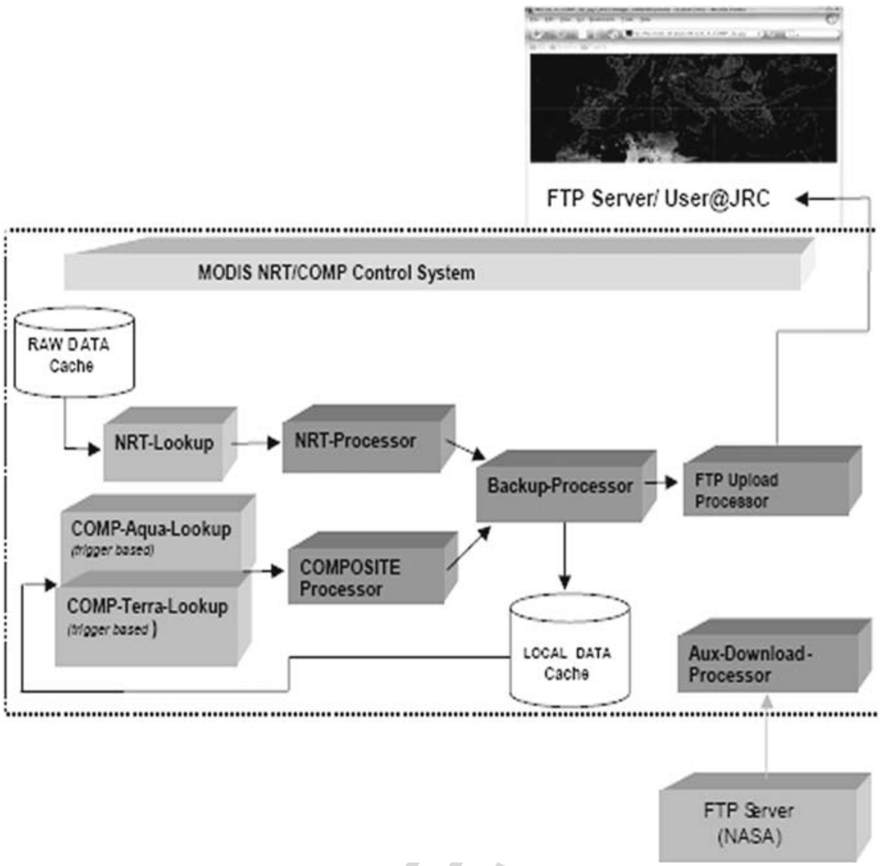


**Fig. 13.3** Pre-processing of MODIS data for EFFIS

imagery reception at DLR and the transmission of the derived products to JRC is presented in Figure x. Daily, two full set of tiles covering the European territory are processed and single pass images and European mosaics are transmitted to EFFIS. These include radiometrically calibrated, geolocated and atmospherically corrected reflectances. In addition, the MODIS thermal activity product is processed. This product is further filtered with the use of the CORINE land cover database and other ancillary datasets within EFFIS with the aim of reducing to the maximum the number of false alarms and distinguish forest fires from other types of fires (e.g. agricultural).

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The active fire product is use for the automatic geo-location of active fires. These fires are visually verified, and the processing of the images continues for those true fires with the aid of a seeded region-growing algorithm (Salvador et al. 2002). The spatial resolution of the MODIS data permits the mapping of fires of approximately 40 ha or larger, although fires of smaller size are often detected and mapped. The

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information on the perimeters of these fires is updated at least daily and available in the "current situation" page of EFFIS. Information is transmitted to the Monitoring and Information Centre of Civil Protection in the Directorate General Environment in Brussels and to the civil protection and forest fire services in the European countries. Currently, the EFFIS network is made up of 23 European countries including EU and neighbour countries. Although a validation exercise was performed in 1998, the validation of the burnt area product from MODIS is on-going, in conjunction with the validation of the global burnt area product of MODIS (Justice et al. 2002). However, this validation was performed in the case of large events as those in Portugal (2003), northwester Spain (2006), and Greece (2007) (Boschetti et al. 2008) and in the case of very large fires such as those in southern Spain and Portugal in 2004, which burnt approximately 25,000 ha, each. The example of AWiFS-based burnt areas for the Peloponnese peninsula (Greece) in the summer of 2007 is presented in Fig. 13.4.

## 13.6 The Way Ahead

The availability of high-frequency and high-spatial resolution remotely sensed data opens new alternatives for the fast and accurate mapping of burnt areas. New methods are currently tested for the combination of multiple data sources for the mapping of burnt areas at high and medium spatial resolution.

In relation to the mapping of burnt areas for the Mediterranean region, two approaches are possible. One is the aggregation of national datasets obtained from the mapping of burnt area from high-spatial resolution imagery. Portugal and France have set up systems to map all fires on the basis of high resolution imagery. European processes such as INSPIRE, which aims at the harmonization of all spatial data at the European level will provide a definite impulse to this approach.

At the European level, the EFFIS will provide maps of burnt areas on the basis of AWiFS from the year 2009 onwards. Testing of alternative datasets such as the Disaster Monitoring Constellation (DMC) is also on-going. This capability will permit the mapping of fires that affect areas of approximately 5 to 10 ha or larger. Burnt areas all Europe will be mapped with high spatial resolution imagery at the end of the normal fire season, around the end of September, every year.

As mentioned in the previous section, at the European level, burned areas of approximately 40 or larger are currently mapped in the European Forest Fire Information System through the processing of MODIS imagery of 250 m spatial resolution. Even though MODIS can, in optimal conditions, detect hot-spots that are smaller than its pixel size (i.e. 1,000 m for the active fire detection product), the current spatial resolution used for burned area mapping (250 m) does not allow accurate estimation of the burned area of relatively small fires (5–40 ha). To overcome these limitations, higher spatial resolution data needs to be used.

A new method for the accurate delineation of burned areas of size of 5 ha or more is currently under development in EFFIS. The method is based on combined

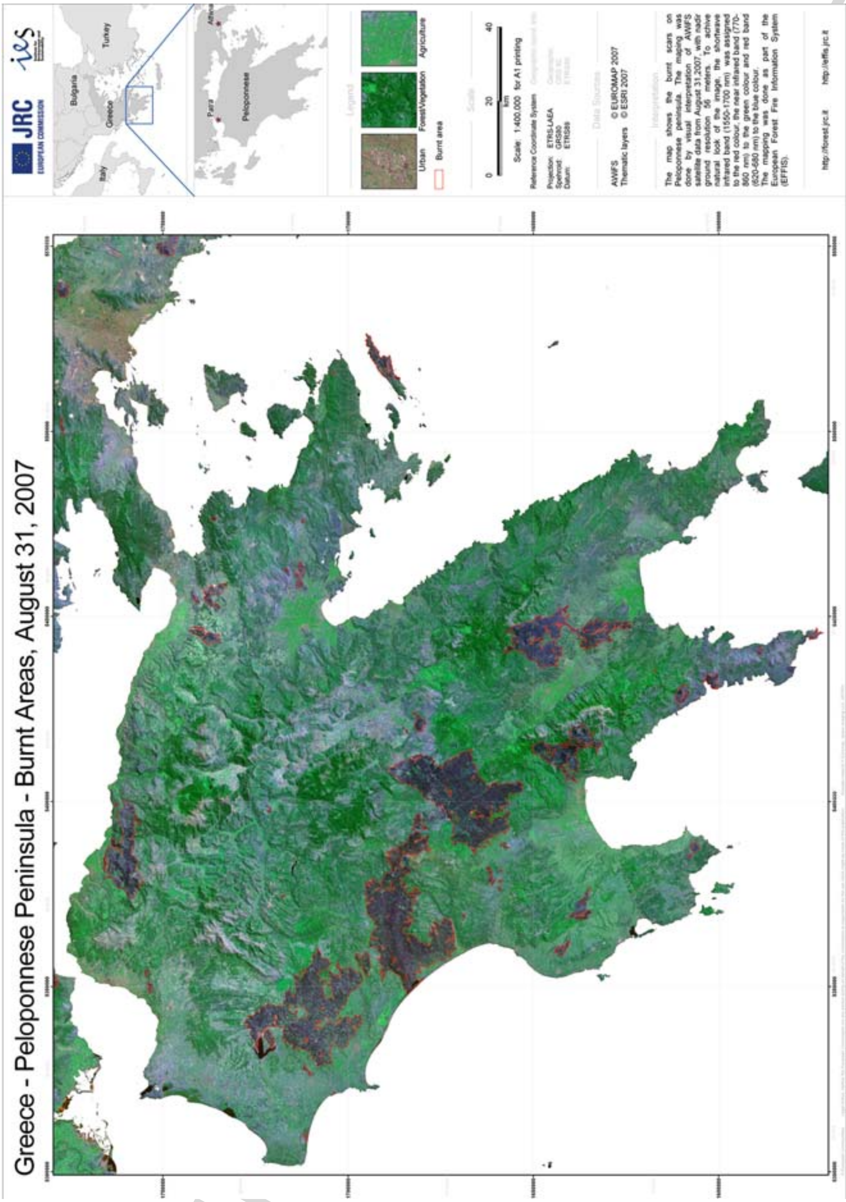


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**Fig. 13.4** Maps of burnt areas in the Peloponnese peninsula (Greece)*

*For colour version of this figure, please refer Colour Plate Section.

use of MODIS and AWiFS images. The AWiFS sensor has a ground spatial resolution of 56 m and it is equipped with four spectral bands, blue (0.52–0.59 $\mu$m), red (0.62–0.68 $\mu$m), near-infrared - NIR (0.77–0.86 $\mu$m) and short-wave infrared-SWIR (1.55–1.70 $\mu$m). The mapping of burnt areas is carried out in two phases. First, a coarse initial wall-to-wall daily burned area mask (BAM) is obtained from MODIS time series (Kucera et al. 2007) and a semi-automatic burnt area mapping procedure. This intermediate product is visually controlled and refined. Further, in a second phase, the BAM is used to train a AWiFS-based burned-area-mapping algorithm. The combined used of MODIS and AWiFS allows the synergistic use of by both sensors. The higher spectral information in MODIS is combined with the larger spatial resolution in AWiFS, which leads to an enhanced mapping of the areas burned by small fires.

At the moment, three different algorithms for burned area mapping from AWiFS have been developed and are currently under evaluation. These are, namely (1) an index based (2) an unsupervised and (3) a supervised algorithm. In the index-based approach, the coarse resolution BAM is used to find appropriate thresholds for indices computed from the AWiFS image. The unsupervised classification algorithm is based on clustering and segment-level spatio-spectral analysis of the AWiFS characteristics of the delineated burned areas. Finally, the supervised approach is based on the extraction of burned and non-burned prototypes from the AWiFS imagery using the BAM, followed by a k-nearest neighbor classification. All the three algorithms are potentially applicable for mapping burnt areas and seem, through a preliminary evaluation, able to produce reliable results. Therefore the final decision among them will be based on a careful analysis of the resulting burned-area maps and the computational performance of the algorithms. The example of MODIS-derived burnt area, subsequently refined with AWiFS data, is presented for the large burned areas in Greece in the summer of the year 2007.

# Chapter 13

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| AQ16 | Please specify whether “Justice et al. 2002” is “2002a” or “2002b”. |
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# Colour Plate Section

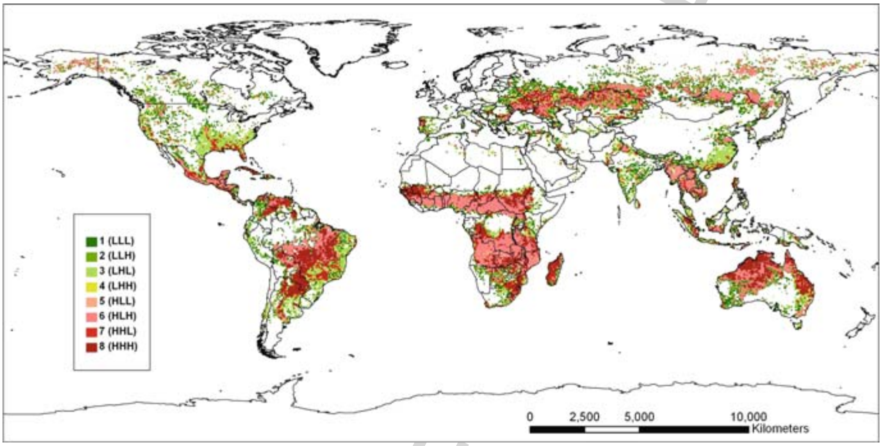



**Fig. 1.3** Classification of fire regimes. H refers to high values and L to Low values and the order of columns accounts for Fire Density, Duration and Variability, respectively (adapted from Chuvieco 2008 #5016)

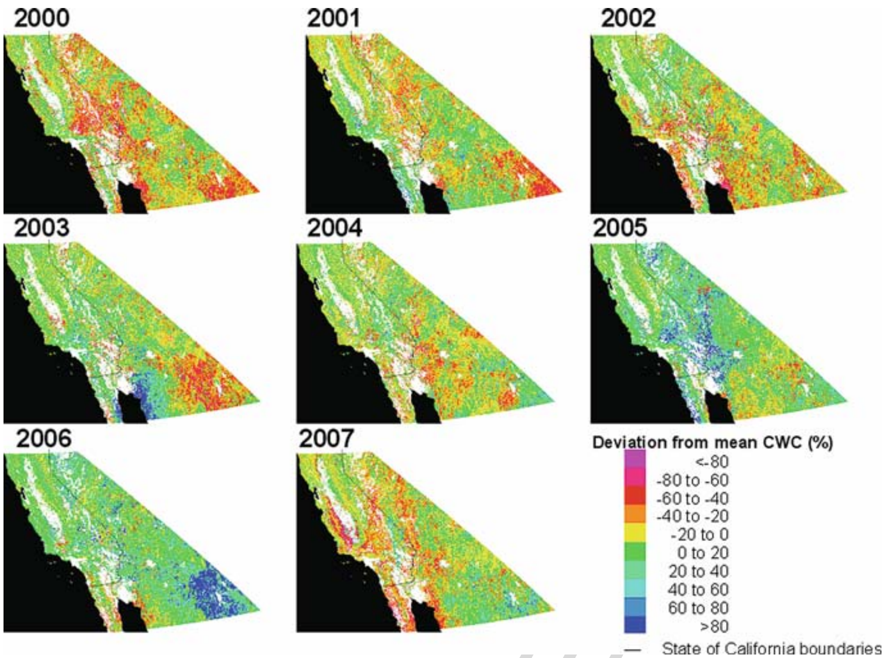
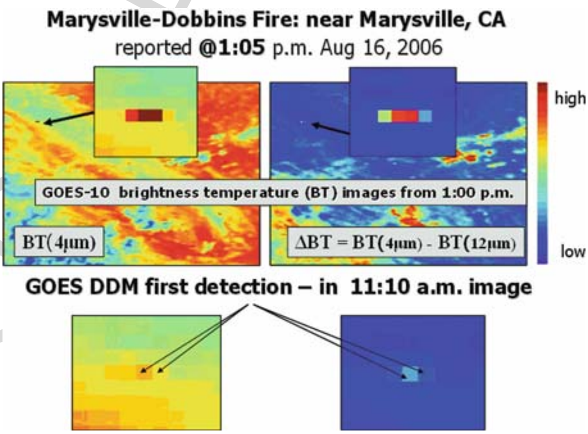



**Fig. 4.3** Percentage deviation for each year from the mean CWC (2000–2007) calculated for the week preceding the San Diego wildfires which began on October 21st, 2007. CWC was calculated from MODIS Terra 8 day composites (MOD09A1) version 5, October 8–15th, 2000–2007 using the method of Trombetti et al. (2008). Only natural vegetation pixels with valid CWC estimates for all years were considered

**Fig. 4.4** Example of early detection of a real wildfire by applying two multitemporal Dynamic Detection Model-based detectors to geostationary GOES-10 Imager data (see also Table 4.1)



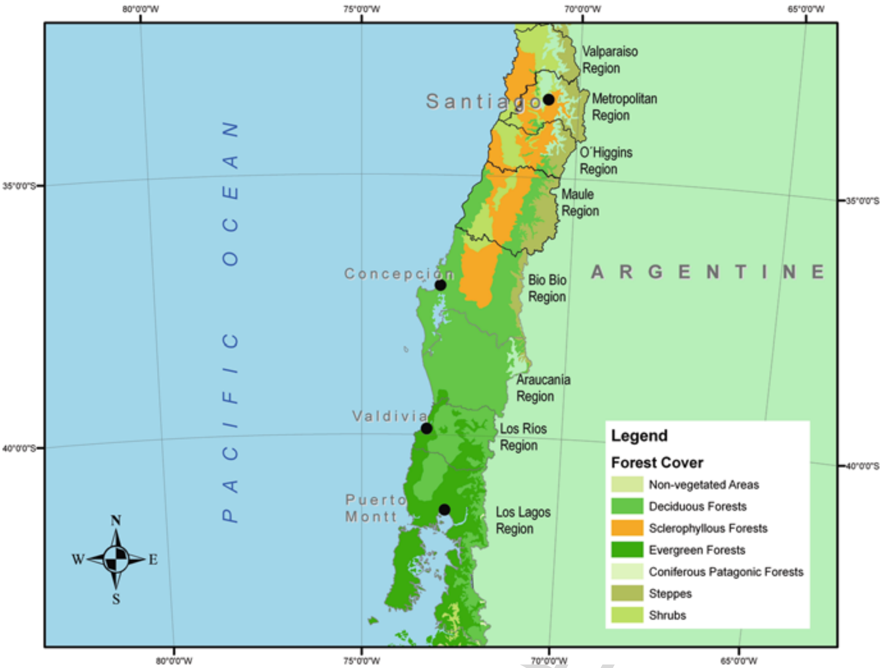



**Fig. 5.1** Vegetation classes in the Mediterranean climate region of Chile, along with administrative regions

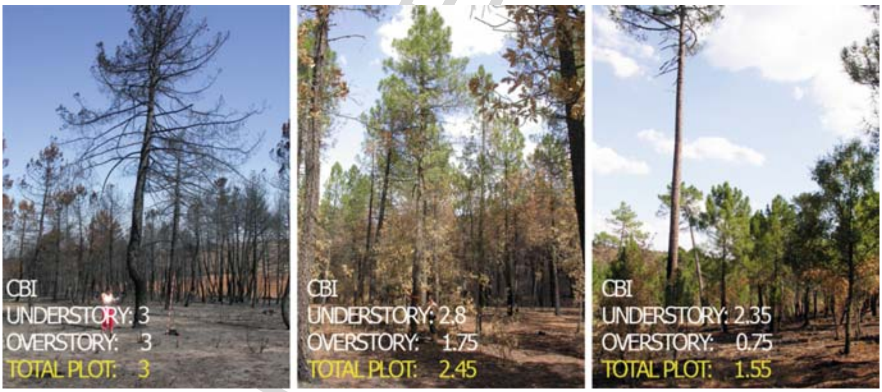



**Fig. 10.1** Examples of high, moderate and low burn severity values observed in the field

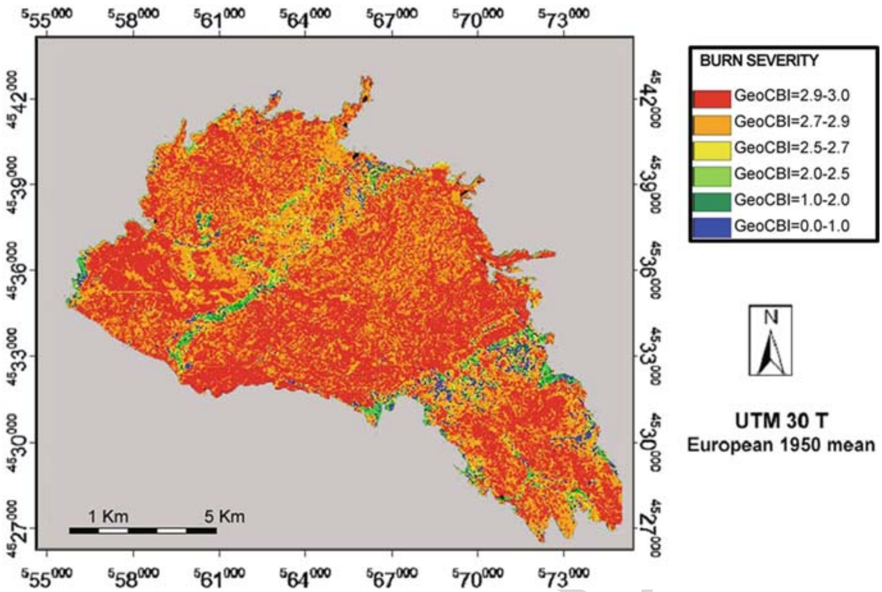



**Fig. 10.3** Example of a burn severity map obtained from the inversion of the simulation model proposed by De Santis et al. (2009)

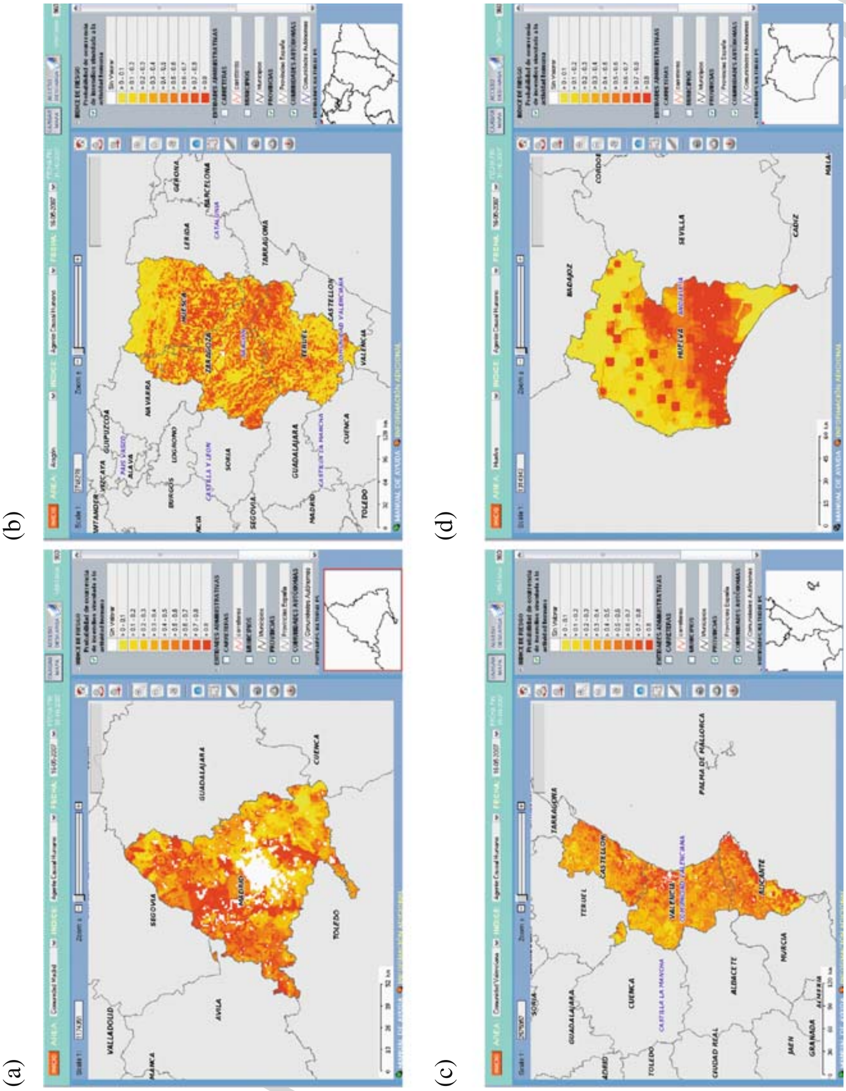
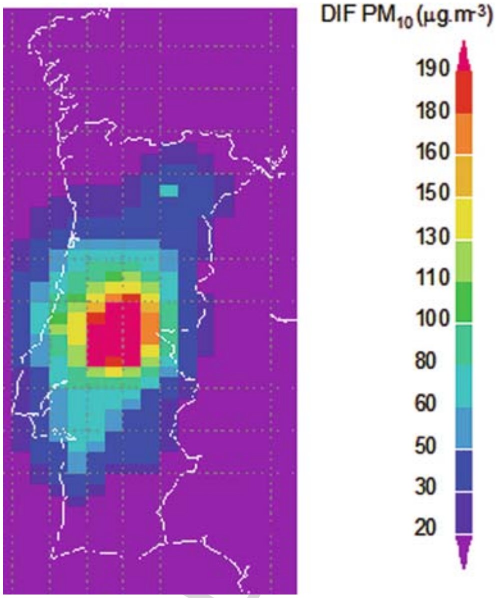



**Fig. 11.5** Human fire risk probability map as included in the FIREMAP map sever. Madrid region (**a**), Aragon region (**b**), C.Valenciana region (**c**), Huelva region (**d**). http://www.geogra.uah.es:8080/cartofire

**Fig. 12.8** Spatial differences of $PM_{10}$ daily means (µg m–3) between simulation with (FS) and without (BS) forest fire emissions, for the 3rd of August



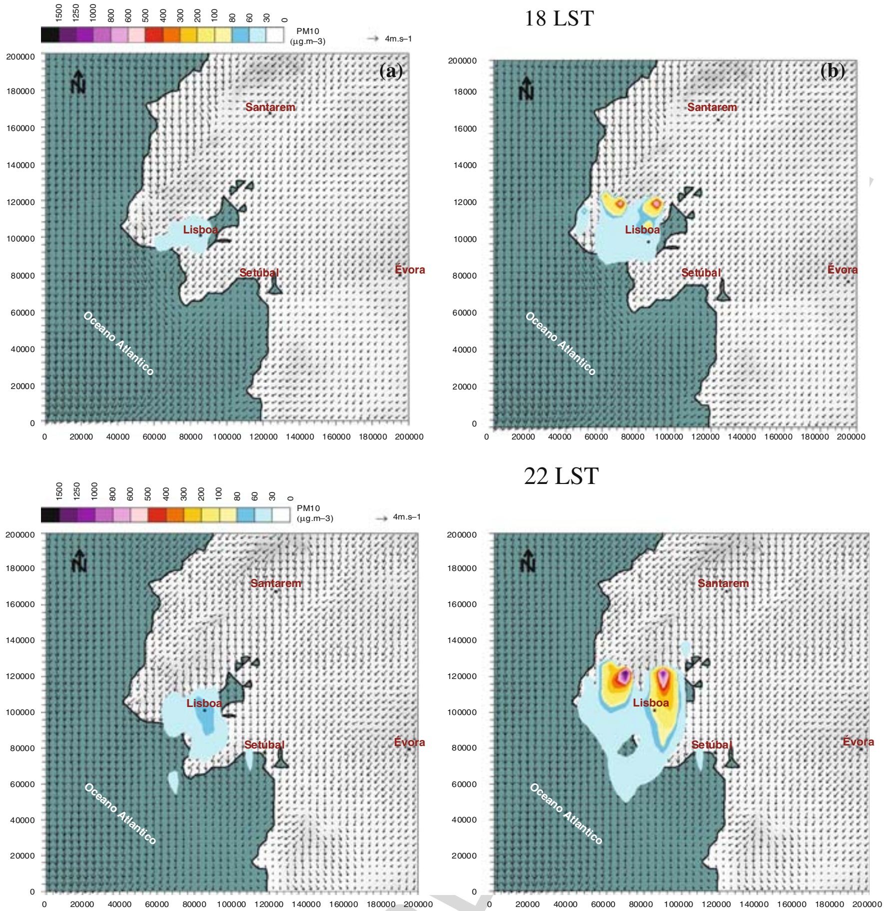
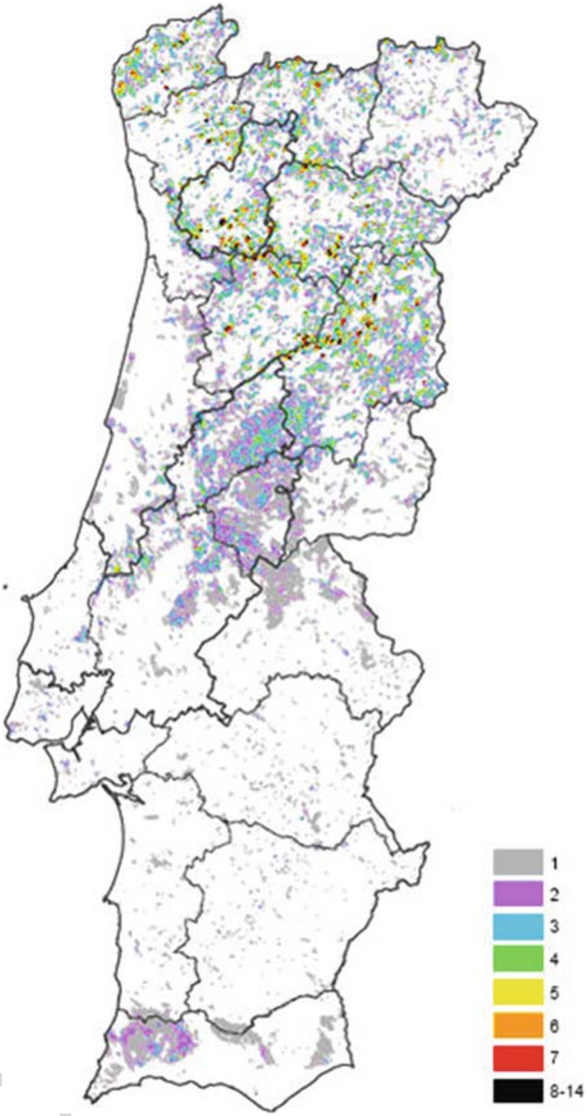



**Fig. 12.9** Wind and $PM_{10}$ ($\mu g\ m^{-3}$) concentration fields at 18:00 and 22:00 Local Standard Time considering: (i) only Lisbon emissions, and; (ii) Lisbon and fire emissions

**Fig. 13.2** Number of times burned, 1975–2005 (from Oliveira 2008)



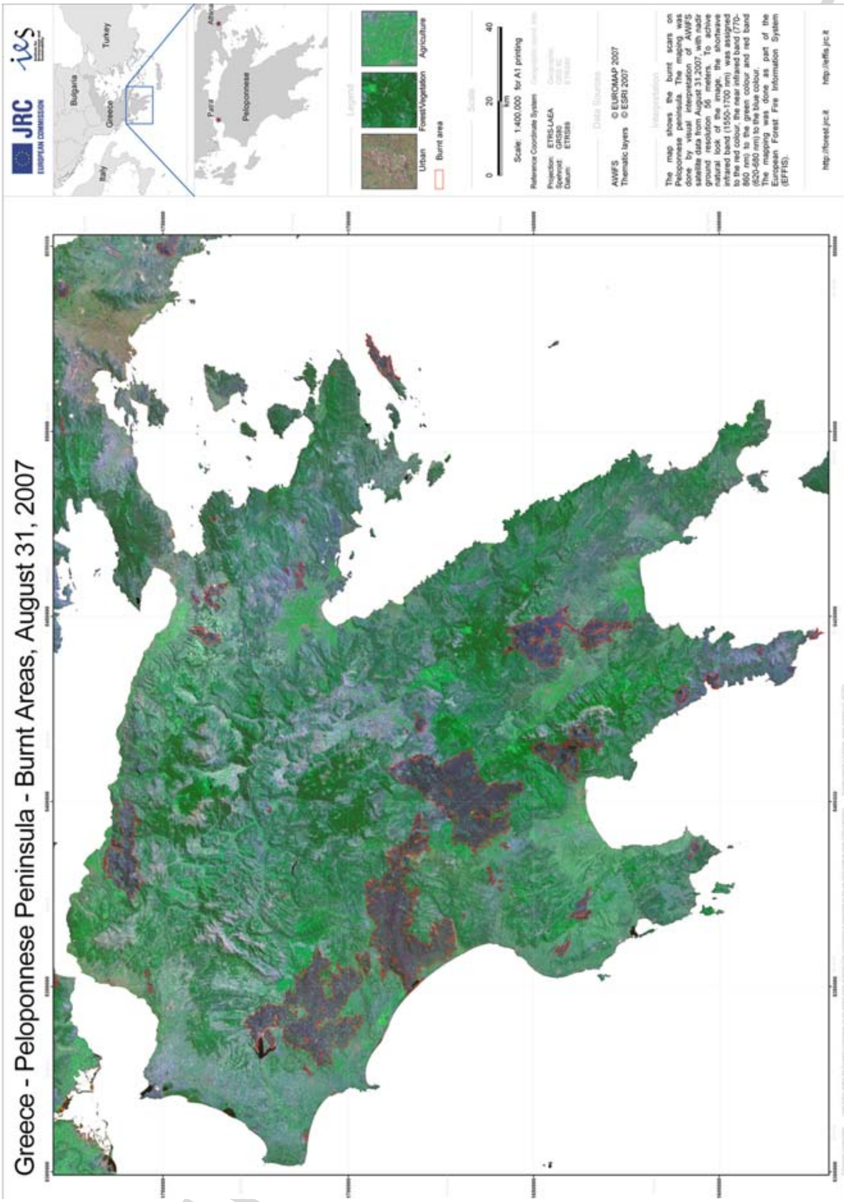



**Fig. 13.4** Maps of burnt areas in the Peloponnese peninsula (Greece)